



**AFRL-RX-WP-TR-2012-0480**



## **COMPONENT, CONTEXT AND MANUFACTURING MODEL LIBRARY (C2M2L)**

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**Pennsylvania State University**

**MARCH 2013  
Final Report**

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## **1.0 EXECUTIVE SUMMARY**

ARL Penn State has developed a manufacturing model library of manufacturing processes and resources typically used to create military ground vehicle drive train and mobility systems. While developing the library, the project team developed a methodology for the development of the models, then used that methodology to create populated models with real data and information. These models will be used by the iFAB Foundry performer for manufacturability analysis and foundry configuration.

Manufacturing models are comprised of both *process* models and *resource* models. The project team completed manufacturing models for Welding, Casting, Forging, Ausforming (heat treatment), Coatings (organic and inorganic), Sheet and Plate Metal Cutting, Material Handling, Dimensional Inspection and Control, and Wire Harness Assembly. In addition, we extended the process models developed by the iFAB performers with detailed resource models of the machines, labor, tooling, fixturing, etc. for the following manufacturing processes: Machining, Additive Manufacturing (Direct Digital Manufacturing), Assembly, and Forming. The addition of these manufacturing process and resource models to the iFAB manufacturing model library encompassed a substantial portion of the manufacturing processes required for the drivetrain and mobility subsystems of an amphibious fighting vehicle.

### **1.1 Definitions and List of Acronyms**

DARPA – Defense Advanced Research Projects Agency

DoD – Department of Defense

AVM – Adaptive Vehicle Make

iFAB – Instant Foundry Adaptive through Bits

MML – Manufacturing Model Library

C2M2L – Component, Context, and Manufacturing Model Library

OPM – Object Process Methodology

DDM – Direct Digital Manufacturing

IFV – Infantry Fighting Vehicle

FANG – Fast Adaptable Next Generation (Ground Vehicle)

CNC – Computer Numerically Controlled

XML – Extensible Markup Language

DB – Database

CAD – Computer Aided Design

## **2.0 INTRODUCTION**

The Adaptive Vehicle Make program aims to revolutionize the design-manufacturing process, specifically for Department of Defense (DoD) weapon systems. The fundamental notion of this aim is to drastically improve the modeling and analysis capabilities in the design and manufacturing functions to accurately and precisely predict performance from an operative vehicle perspective and from a manufacturing lead time and cost perspective. Therefore, it is imperative that models be developed that can be used for a wide range of analyses. The Component, Context, and Manufacturing Model Library (C2M2L) program was commissioned to develop and populate the models needed in these analyses.

The manufacturing model library portion of C2M2L is the focus of the work presented in this final report. Robust and somewhat comprehensive library structures were developed in the Instant Foundry Adaptive through Bits (iFAB) program, a previous and complementary effort under the AVM portfolio of programs. The work presented in this report reflects the efforts of the Applied Research Laboratory at the Pennsylvania State University to develop manufacturing models that are used to populate those library structures with the information required to construct a drive train and mobility system.

### **2.1 Problem**

The goal of the Adaptive Vehicle Make (AVM) portfolio of programs is to reduce the development cycle of a military ground vehicle by at least a factor of five. To accomplish this goal, significant improvements to the enabling infrastructure for design, verification and manufacturing processes modeling must be achieved. In light of this, AVM seeks to develop novel modeling and analysis tools and instantiate models of the set of manufacturing processes relevant for an infantry-fighting vehicle.

### **2.2 Solution**

To support the rapid synthesis of foundries and their reconfiguration, it is important to build an iFAB Manufacturing Process Capability Library, or Manufacturing Model Library (MML). Our development of manufacturing models has augmented the iFAB MML by including the following:

1. Manufacturing process characterization
2. Manufacturing resource characterization
  - a. Performance characterization
  - b. Constraint characterization

We have characterized manufacturing *processes* and *resources* for:

- Welding
- Casting
- Forging
- Ausforming

Note: Ausforming Manufacturing Model development was substituted with post heat treatment process models due to the specific application of Ausforming to gear manufacturing.

- Organic Coatings
- Inorganic Coatings
- Sheet and Plate Metal Cutting
- Material Handling
- Dimensional Inspection and Control.
- Wire Harness Assembly

The project team has also extended the process models developed by the current and past iFAB and C2M2L performers with detailed *resource* models for:

- Machining
- Additive Manufacturing (Direct Digital Manufacturing)
- Assembly
- Forming

The manufacturing resources at Penn State University, under the above process classes that would be made available to future programs under AVM for the purpose of fabricating and assembling components and assemblies of an infantry fighting vehicle, have been characterized and included in the MML. These resources are composed of machines and processing facilities at the Applied Research Laboratory shops and prototype labs, the Factory for Advanced Manufacturing Education (*FAME*) laboratory in the Industrial and Manufacturing Engineering Department, and the Learning Factory in the College of Engineering. All told, we have characterized and populated the MML with the attributes of over 50 machines and manufacturing processing facilities at Penn State.

In the global manufacturing industry, there are thousands of alternative processes available for producing components. However, much of the process knowledge, process steps, resource requirements, tolerances, capacity, etc., resides within process domain experts. There is no pervasive manufacturing process knowledge repository available for design and manufacturing engineers. Therefore, process planners cannot easily obtain the information required to establish a foundry capable of manufacturing a military ground vehicle, or to provide information to designers on manufacturing cost and capability. The developed MML will support the established AVM framework for such a repository by populating the process and resource models necessary to define the Manufacturing Model Library for the drivetrain and mobility subsystems of a military ground vehicle.

### 3.0 METHODS, ASSUMPTIONS, AND PROCEDURES

The purpose of this project was to develop a manufacturing model library (MML) that contains information and logic about the previously stated manufacturing processes and resources. It was assumed that the information contained in the developed MML would be subsumed in another more robust library developed by previous AVM iFAB performers that used a more extensive query and logic engine for process planning and manufacturability analysis. The following sections describe the manufacturing model development methodology/process.

#### 3.1 Manufacturing Model Methodology

A manufacturing model describes the processes by which a component is made. Integral to the processes are the specific resources used for each process. A complete manufacturing model has the ability to provide feedback to designers and foundry configurators in terms of constraints and performance metrics.

*Process modeling* entails the characterization of the process routings, i.e. steps, generic class of resource requirements, metrics, and other process support requirements. General process models can be developed for any process, and each step or set of steps in the process typically requires a resource or set of resources to perform the operation. In this manner, a process can often be performed by many alternative resources.

*Resource characterization* identifies the machine or machines (or people, assembly stations, etc.) that are used for the corresponding processes identified. This will also include tooling, fixturing, energy requirements, auxiliary equipment, and maintenance processes needed. The resources will set the process capability, establish the process constraints, and define the performance of the process. Most importantly in this step, we identified the set of alternate processes for which a machine (or other resource) can be used. Resource characterization also enables the following:

*Performance characterization* is the process of identifying the performance of a process in terms of cost, throughput, quality, adaptability, and controllability. Given a general process model and specific resources at each of the process steps, the process will have performance characteristics that can be used by iFAB Foundry for foundry configuration.

*Constraint characterization* is the process of establishing the constraints of the process and resource combination in terms of part size, materials, tolerance capability, weight, and shape. Some of the constraints are inherent in the general manufacturing process (e.g., cannot friction stir weld steel), however the resources selected to perform the operations in the general process define additional constraints on the overall process. For example a CNC turning process may be capable of producing parts to  $\pm 0.005\text{in.}$ , but if the actual CNC turning center, e.g. Haas SL20T CNC Lathe chosen for the operation only has the capability to produce parts to  $\pm 0.0075\text{in.}$ , then the process is constrained to  $\pm 0.0075\text{in.}$

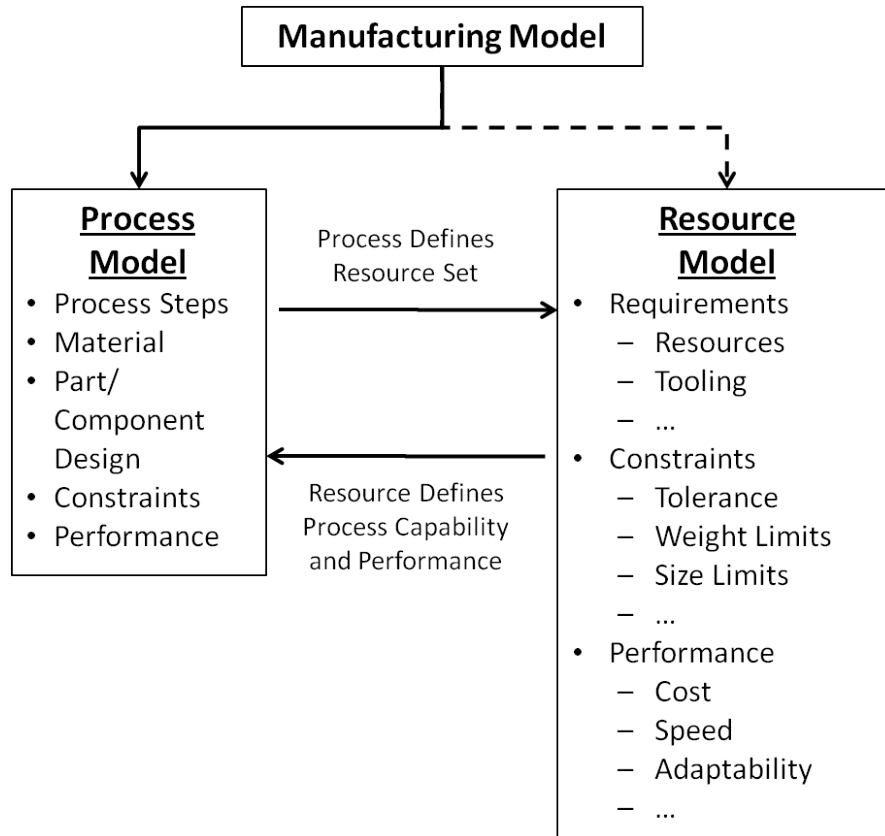
Models in the Manufacturing Model Library will be exercised by the iFAB Foundry tools and methodologies and should be able to completely describe and characterize all of the process elements required to manufacture/assemble a specific product. The models need to be able to

define the constraints of the process in terms of part size, production rate, weight, material, tolerance, finish, etc. These constraints will be used by the iFAB Foundry and FANG design participants to define the vehicle design and construction processes.

Additionally, these manufacturing models should be used to support the configuration of a foundry, which includes the ability to perform process simulation at three levels of detail. The first level facility modeling is the initial factory (foundry) layout for high-level (facility planning) type design and layout. The second level is process flow type modeling, typically modeled as a discrete event simulation model, where the high-level facility model is refined and modified for throughput, WIP, buffering, and capacity type concerns. The last and most detailed level of modeling that these models must support is detailed work instructions/ergonomic modeling. These three levels fully describe the development of a facility, or network of facilities, to manufacture a military ground vehicle.

Process models take on many forms and model various levels of detail. For example, the process to manufacture a gear is actually a collection of processes that include: creating the blank, cutting the teeth, heat treating, and final finishing. Each of these process steps is an independent process, combined to manufacture a gear. These processes have characteristics that provide manufacturing constraints, capabilities, and support activities to the gear manufacturing process as a whole.

The general form of the proposed manufacturing model is shown in Figure 1. As discussed, a manufacturing model is comprised of a process model and a resource model. The process model includes the basic process steps along with the generic class of resource assignments and requirements. For example a machining process may simply be [insert raw stock into fixture→load CNC code→insert tool→run CNC code→remove finished part from machine]. The fully detailed process model would include the unique machine to be used, its manning requirements, i.e. a machinist with specialized skills, and the tooling and fixturing required.



**Figure 1: Manufacturing Model Diagram**

The process model and the resource model for the process define the process constraints (tolerances, material types, part sizes, etc.). The process constraints are set, in part, by the type and model of the machine, the materials being used, the tools used for processing, and the skills and abilities of the machinists operating the machines,

We have built a lightweight MML that is populated using a modeling schema that embraces the various levels of detail in a nested or hierarchical fashion. Figure 2 shows the proposed manufacturing process modeling description language that includes the ability to model the resources, performance measures, and constraints of the process.

```

<xs:schema xmlns:xs="http://www.w3.org/2001/XMLSchema">
  <xs:complexType name="process">
    <xs:sequence>
      <xs:element name="id" type="xs:long" />
      <xs:element name="process_step" type="xs:long" minOccurs="0" maxOccurs="unbounded" />
      <xs:element name="resource" type="xs:long" minOccurs="0" maxOccurs="unbounded" />
      <xs:element name="constraints" type="constraintsType" />
      <xs:element name="performance" type="performanceType" />
    </xs:sequence>
  </xs:complexType>
  <xs:complexType name="resource">
    <xs:sequence>
      <xs:element name="id" type="xs:long" />
      <xs:element name="resource" type="xs:long" minOccurs="0" maxOccurs="unbounded" />
      <xs:element name="constraints" type="constraintsType" />
      <xs:element name="performance" type="performanceType" />
    </xs:sequence>
  </xs:complexType>
</xs:schema>

```

**Figure 2: Manufacturing Model Description Language.**

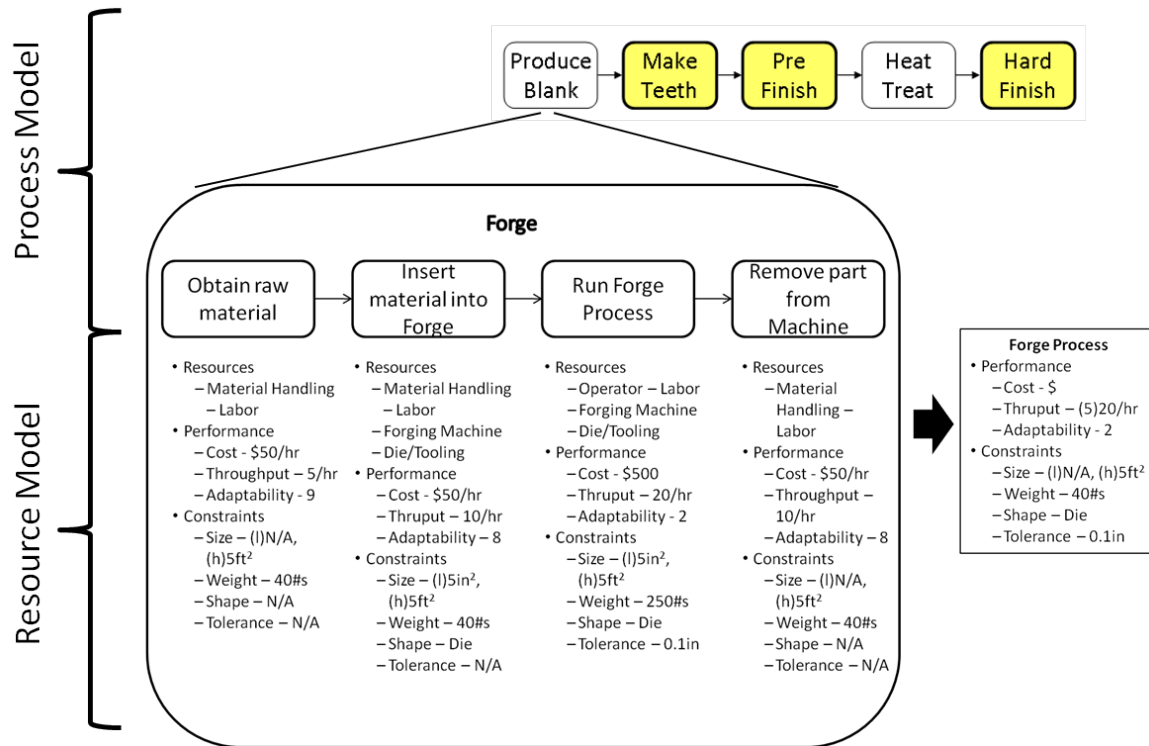
A manufacturing model is a data structure that defines the process steps, resources, performance measures, and constraints of the process. The resources chosen to perform the process steps somewhat define the performance measures and the process constraints. Therefore, we define the resource model as the characterization of the resources that can be used to perform the work in the containing process model. The purpose of this is twofold; first, a resource model can be incorporated into or referenced by many different process models, and second, there were performers in the iFAB program (GA Tech, Boeing) that were developing process models of many processes, and the resource models developed here could be used to annotate and extend those process models, making more physical machines and facilities available to iFAB Foundry.

The model format is based on an XML schema that is both extensible and flexible, in addition to being easily integrated into other models or converted into other formats. Additional attributes of the process can be added easily and more detailed processes can be defined and simply replace high-level process definitions in the schema.

### **3.1.1 Example Manufacturing Process and Resource Model: Transmission Gear**

Consider the manufacturing of transmission gears. The main process steps in manufacturing gears are illustrated at the top of Figure 3.





**Figure 3: Process and Resource Model Example.**

Figure 3 shows an illustrative high-level process for manufacturing a gear along with a detailed illustrative process model for the first step in the process (producing the blank). Notice that a forging process has been selected to produce the blank and that there are four process steps. The resources required for each of the process steps are also shown in Figure 3. The process performance metrics and constraints are products of the resources selected for each of the process elements. The performance measures and constraints for each of the process steps “roll up” to form overall process performance and constraints that can be disseminated internally while generating foundries and externally to FANG Design Challenge Participants for manufacturability feedback. It should also be noted that the performance and constraint attributes shown are a representative set of attributes and not an exhaustive list.

The specific attributes to define a resource will vary. For instance, a welder (i.e., human labor) will have attributes for special certifications, but would not need an attribute for tolerance capability like a CNC machine would. In addition, performance and constraint attributes may be represented by a distribution rather than a deterministic number. Figure 4 shows the resulting data model for the example shown in Figure 3.

```

<manufacturingModel>
  <process id="10000" name="Manufacture Gear">
    <process_step>10001</process_step>
    <process_step depends="10001">10006</process_step>
    <process_step depends="10006">10007</process_step>
    <process_step depends="10007">10008</process_step>
    <process_step depends="10008">10009</process_step>
  </process>

  <process id="10001" name="Produce Blank">
    <process_step>10002</process_step>
    <process_step depends="10002">10003</process_step>
    <process_step depends="10003">10004</process_step>
    <process_step depends="10004">10005</process_step>
  </process>

  <process id="10002" name="Obtain Raw Material">
    <resource>20001</resource>
    <constraints>
      <constraint name="height" unit="feet">5</constraint>
      <constraint name="weight" unit="pound">40</constraint>
    </constraints>
    <performance>
      <costs>
        <cost name="unit_cost" unit="dollars">50</cost>
        <cost name="startup_cost" unit="dollars"><triangular lower="450" upper="550" mode="500" /></cost>
      </costs>
      <throughput unit="hour"><triangular lower="4" upper="6" mode="5" /></throughput>
      <adaptability>9</adaptability>
    </performance>
  </process>

  <process id="10003" name="Insert Material into Forge">

  <process id="10004" name="Run Forge Process">
    <resource>20002</resource>
    <constraints>
      <constraint name="length" unit="inch">5</constraint>
      <constraint name="height" unit="feet">5</constraint>
      <constraint name="weight" unit="pound">250</constraint>
      <constraint name="shape">20003</constraint>
      <constraint name="tolerance" unit="inch">0.1</constraint>
    </constraints>
    <performance>
      <costs>
        <cost name="unit_cost" unit="dollars"><triangular lower="450" upper="550" mode="500" /></cost>
        <cost name="startup_cost" unit="dollars">50,000</cost>
      </costs>
      <throughput unit="hour"><triangular lower="15" upper="25" mode="20" /></throughput>
      <adaptability><gaussian mean="2" stdev="0.5" /></adaptability>
    </performance>
  </process>

  <process id="10005" name="Remove Part from Machine">

  <process id="10006" name="Make Teeth" />
  <process id="10007" name="Pre Finish" />
  <process id="10008" name="Heat Treat" />
  <process id="10009" name="Hard Finish" />

  <resource id="20001" name="Material Handling - Labor" />

  <resource id="20002" name="Forging Machine">
    <resource>20003</resource>
    <resource>20004</resource>
  </resource>

  <resource id="20003" name="Die/Tooling" />

  <resource id="20004" name="Operator - Labor" />
</manufacturingModel>

```

Figure 4: Example XML Model

### **3.1.2 Manufacturing Model Definition and Instance Population**

The objective of this portion of the project was to determine OPM's effectiveness in helping to describe a manufacturing process with sufficient detail to understand and communicate the requirements of that process to produce a given part. Also this portion of the research is to show that by utilizing Object Process Methodology (OPM), a manufacturing system can be detailed, and using some of the tools in OPM, the system can be verified while being built. Additionally, the scope of the model can be augmented and changed by utilizing the scaling tools without changing the base model, facilitating deeper and richer analysis.

#### **3.1.2.1 Manufacturing Model Definition Using OpCat**

Initially, process experts constructed the models with assistance of an experienced OPM user using the OPCAT (<http://www.opcat.com/>) software system (version 4.0). As the project progressed, the process experts could produce these models on their own. OPM consists of two methods of representation, the Object Process Diagram (OPD) and the corresponding Object Process Language (OPL) sentences. OPCAT allows for a system to be built either graphically or using the OPL sentences. Both the graphical and the language portions are generated together, giving the users two methods to understand and debug the process. The two description modes used by OPM are semantically equivalent; yet appeal to two different parts of the brain, the visual and the lingual. Additionally, the model is saved as an XML file that can be read into other programs via a short additional program. This tool aids not only the building and debugging of the model, but also the communication of the model to stakeholders, regardless of their process expertise and software requirements.

OPM is built in a hierarchical manner, with the root diagram, called the system diagram (SD) being the most abstract level desired in the scope of the system. The remaining OPD's are built by recursively zooming into processes of interest and each is a more detailed view of its ancestor. For example, the SD for the example model was the "Non-Cored Greensand Casting Manufacturing". The in-zoomed processes went as far as required to adequately describe the process requirements; as well as to provide inputs for optimization analysis for different process choices.

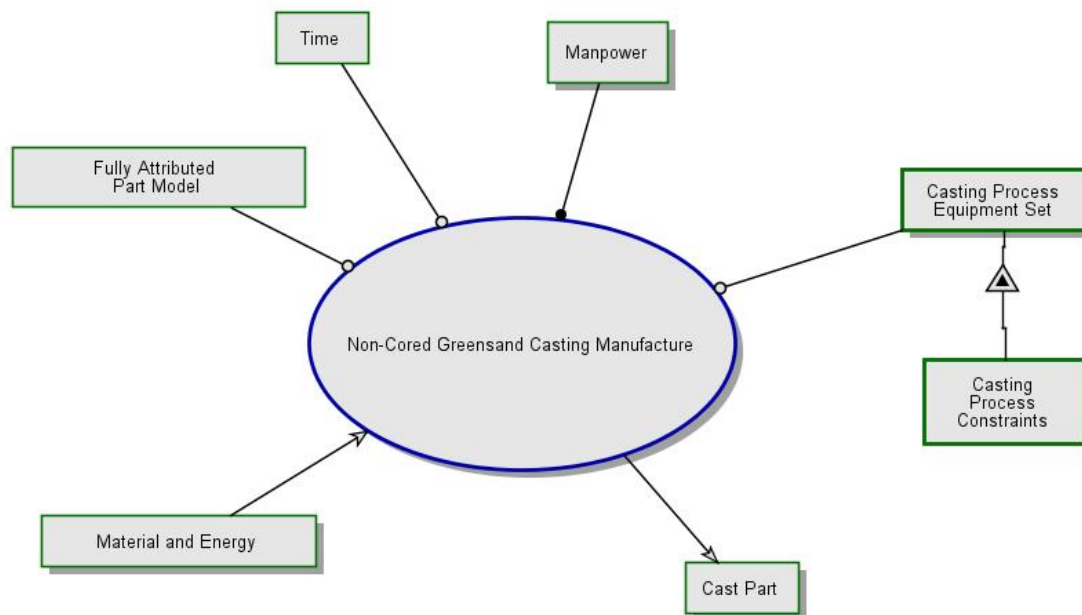
OPM is built with only three types of entities: objects, processes and states, with objects and processes being higher-level building blocks. Objects are defined as a thing that exists or might exist. An object can have states such that at a given point in time an object is in one of its states or in transition between two states. A process is a thing that happens to an object and transforms it. The transformations that can occur to an object are creating an object, consuming an object, or changing an object's state. Additional information can be added by using special symbols that describe the relationship between objects and processes such as aggregation and result links, or describe the objects and processes themselves. While OPM is highly structured in its usage, it is very intuitive. With the aid of OPCAT software prompts model building is a straightforward process.

#### **3.1.2.2 Casting Process Manufacturing Model Example**

The system diagram (SD), shown in Figure 5, for the foundry model begins the modeling process by defining the process that will be modeled and placing it within the context for the model. The process being modeled is the Non-Cored Greensand Casting Manufacture and the context

includes its major inputs and the required product and process parameters for manufacturing an un-cored casting.

In OPM, processes are shown in an oval and objects are shown as rectangles. The methodology allows for more detail to be shown in this simple format. The formatting of a rectangle for an object denotes whether it is in physical or informatical. Intuitively, the shaded rectangle is physical; that is, it casts a shadow. The informatical object does not. Also, the formatting of the rectangle can denote whether an object is part of the system, or part of the system's environment.



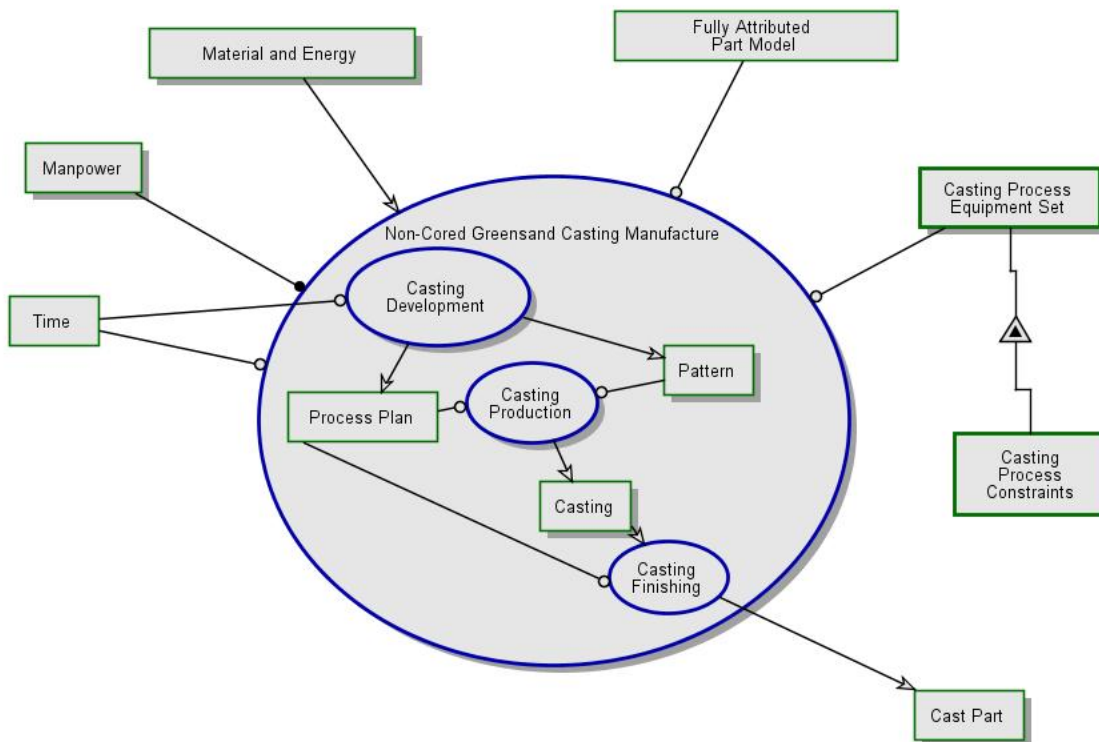
**Figure 5: Casting Example Model System Diagram (SD)**

The model is built top down, so that the next level is an in-zoom of the process “Non-Cored Greensand Casting Manufacture”. It should be noted however, that the OPCAT software allows you to import a model into another model, so that if you expand the scope of the model you can import the existing model in as a lower level abstraction to the expanded model.

Figure 6 shows the in-zoom of the Non-Cored Greensand Casting Manufacture, which would be the first level in the OPD and thus is called SD1. Each level is constructed such that it is understandable with the number of elements pictured is kept to a minimum. This level also defines the scope of the model more clearly, showing that the processes that are included in the model are Casting Development and Production, and Casting Fettling. Originally, the model did not include Casting Development; however, when discussing the future work with process experts, expanding the boundary out was preferred. With OPM / OPCAT it was not difficult to add this process at this level and then develop the subsequent detail.

As this level includes three processes, the next level hierarchically contains three system diagrams (SD), SD 1.1, SD 1.2, and SD 1.3 for each process respectively. Heavier lines around a process mean that process has more detail in the model. As a process is in-zoomed it brings with it the items that were surrounding the parent process. These items can be left in the lower level

OPD, they can become more detailed, or they can be deleted if the specific process at the next level does not require that detail. The OPCAT software keeps track of the relationships. If something is added to a lower level OPD, you are given the choice to reflect that addition in higher-level diagrams. One could also copy an entity from one OPD to another. The software will prompt the user if the addition violates OPM rules. In this way, the user can gain resolution as you go deeper in the process while maintaining the relationships and clarity.

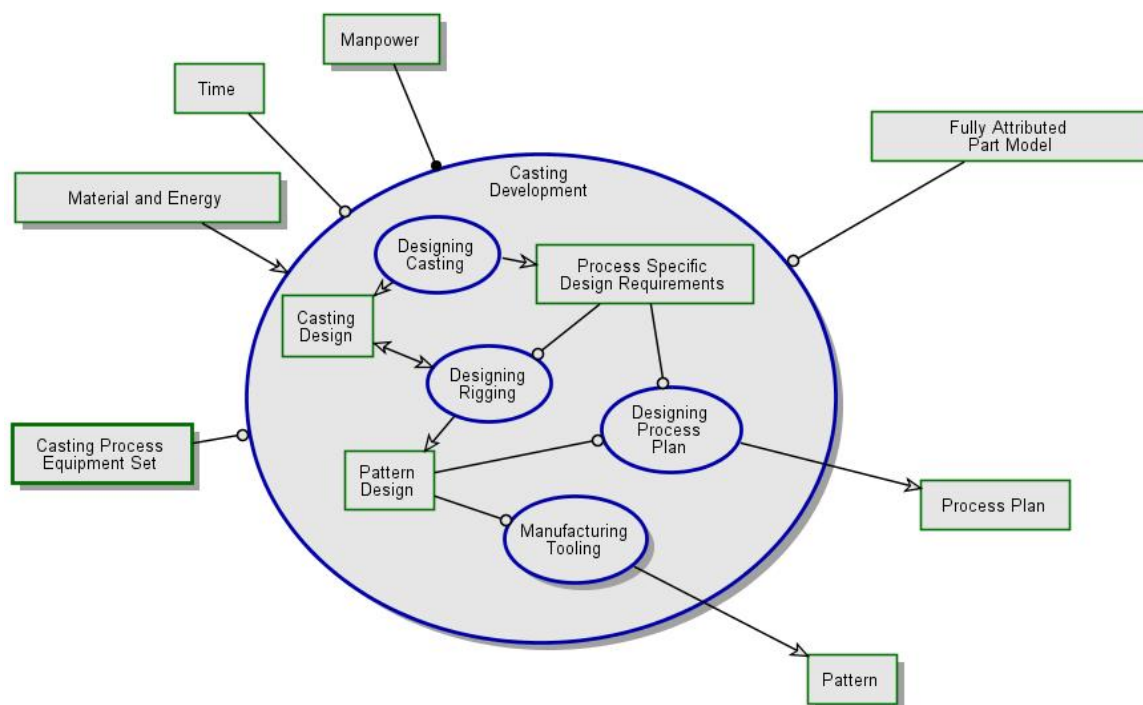


**Figure 6: Casting Example In-Zoom**

Figure 7 shows the in-zoom of the Casting Development Process. This was included in this model to show the time series capability of this modeling methodology such that the entire life cycle for the casting process could be modeled using this tool. In this view, several different types of connections between objects and processes, and objects and objects are shown. The first and most intuitive is the transformation link, which is represented by a line with an arrowhead as is shown between Casting Design and Tooling Model. This shows a result as in the casting design process yields a tooling model. The double headed arrow as is shown between Casting Design and Designing Rigging Process means that the Casting Design is effected by the Designing Rigging Process. These are both procedural links. Another type of procedural link are enabling links. There are three types, agent, instrument, and conditional links, two of which are shown in Figure 7. The agent link is shown by a line with a solid circle at the end as shown between Manpower and Casting Development. The meaning of this is that manpower is required in the casting development process; however, unlike the transformation link, the foundry engineer is not consumed or transformed by the process. The agent is an intelligent enabler which is different than the instrument link, which denotes something that is not an agent. The



instrument link is shown by a line with an open circle as is between Process Specific Design Requirements and Designing Rigging. The process specific design requirements, a piece of information, is required for rigging design. The third type of enabling link is not used in this model, but is a conditional link. Also not used in this model are event links which denote when a process is executed based on an external event. This detailed linking scheme within OPM provides richness in the model without adding clutter.

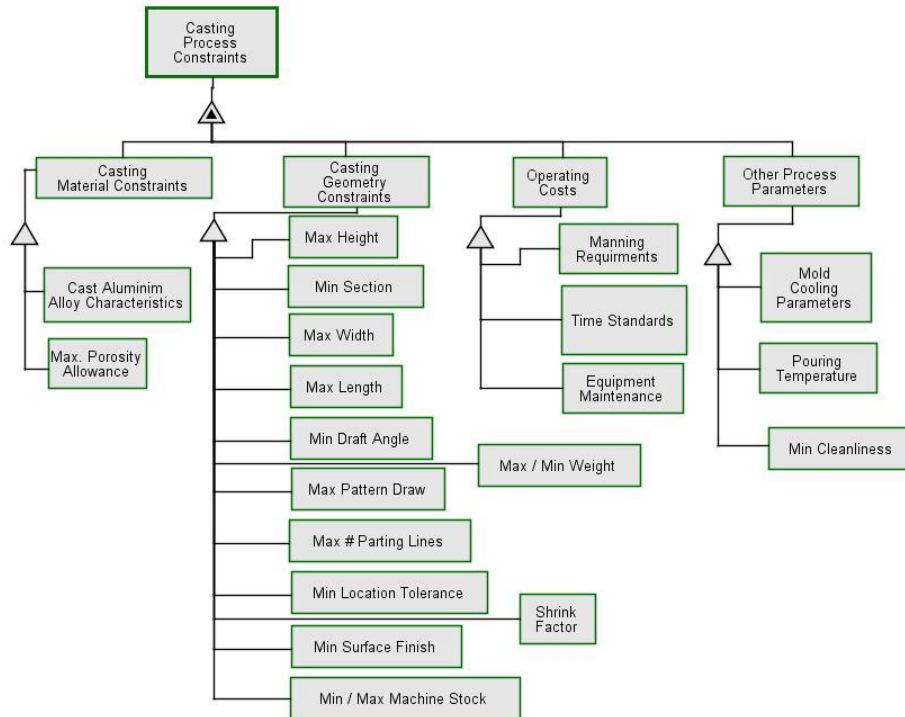


**Figure 7: Casting Example In-Zoom of Casting Development Sub-Process**

In addition to the ability to in-zoom, decreasing the abstraction level of the model, and out-zooming, increasing the distance and thus the scope of what is viewed, the OPCAT software allows a model to be “unfolded”. Unfolding allows you to see what is hierarchically below a component in the model. The casting process constraints are unfolded and shown in Figure 8.

Unfolding can be very helpful in model building in both debugging and in establishing the relationship between components so that when added to the model that relationship remains the same. It assisted in debugging by insuring all the hierarchies and connections made sense for that specific process. The unfolded view of the casting process constraints also allows for a summary of the constraints from different portions of the model.

This view also demonstrates another type of connection that is used in OPM, the structural link. For example in Figure 8 the lines connecting Casting Process Constraints to the four objects on the next level have a solid triangle within an open one. This is a featuring-characterization link, showing that Casting Process Constraints are characterized by these four items.



**Figure 8: Casting Example Unfolded View of Casting Process Constraints**

As stated before, OPM consists of both graphical and language portions. Each nuance that is developed in the graphical portion is reflected in the language portion. This language is either automatically generated when the graphical portion is drawn, or in the version of OPCAT that was used, the graphics can be generated by typing in sentences with the proper syntax. Figure 9 shows the Object Process Language for the Casting Development Process In-Zoom shown in Figure 6. The language is very useful in both debugging the model and providing understanding to the model users. For instance, properly identifying objects and processes can be difficult for process experts who are used to developing Object – Object models. One common error was identifying the equipment required to perform a process as the process itself, instead of considering what the process was doing. Building an OPM model can provide insights into an existing system for process experts. Having two “versions” of the same model, which impact different methods of perception model assists in communicating the model to stakeholders and in finding model inconsistencies.

Material and Energy is physical.  
 Pattern is physical.  
 Manpower is physical.  
 Manpower handles Casting Development.  
 Casting Process Equipment Set is physical.  
 Casting Development is physical.  
 Casting Development exhibits Casting Design and Pattern Design.  
 Casting Development consists of Designing Casting, Designing Rigging, Manufacturing Tooling, and Designing Process Plan.  
 Casting Development requires Time, Fully Attributed Part Model, and Casting Process Equipment Set.  
 Casting Development consumes Material and Energy.  
 Casting Development zooms into Designing Casting, Designing Rigging, Designing Process Plan, and Manufacturing Tooling, as well as Process Specific Design Requirements, Pattern Design, and Casting Design.  
     Designing Casting yields Process Specific Design Requirements and Casting Design.  
     Designing Rigging requires Process Specific Design Requirements.  
     Designing Rigging affects Casting Design.  
     Designing Rigging yields Pattern Design.  
     Designing Process Plan requires Pattern Design and Process Specific Design Requirements.  
     Designing Process Plan yields Process Plan.  
     Manufacturing Tooling is physical.  
     Manufacturing Tooling requires Pattern Design.  
     Manufacturing Tooling yields Pattern.

Figure 9: Casting Example OPL for Casting Development Sub-Process In-Zoom

The modeling process continues until the level of detail is reached where data is available, or that describes the system well enough for the analytical purpose intended. In this instance, the model was being used to verify the Casting Process Constraints data and to identify gaps. One advantage of the OPM / OPCAT model was that some process data was only available at a department level, while other information was available for a specific process within a department. OPM / OPCAT allowed different levels of abstraction within the model depending on the available information.

The objective of this portion of the project was to determine OPM's effectiveness in helping to describe a manufacturing process with sufficient detail to understand and communicate the requirements of that process to produce a given part. Building the varied manufacturing system models demonstrated that OPM is an effective method for this purpose. The dual nature of the model, the OPD and OPL aided with the building and the debugging and communication of the model to stakeholders. The hierarchical views allowed for communication of both the overall scope of the model as well as the level of detail for process specific questions. Because the model could be built by in-zooming on a specific process, it kept single views of the process simple and clear.

The functions in the OPCAT software for creating views by un-folding or finding all the links to a specific object or process allowed for both clarity in communicating the model as well as additional analysis.

In summary, the major benefits of OPM are:

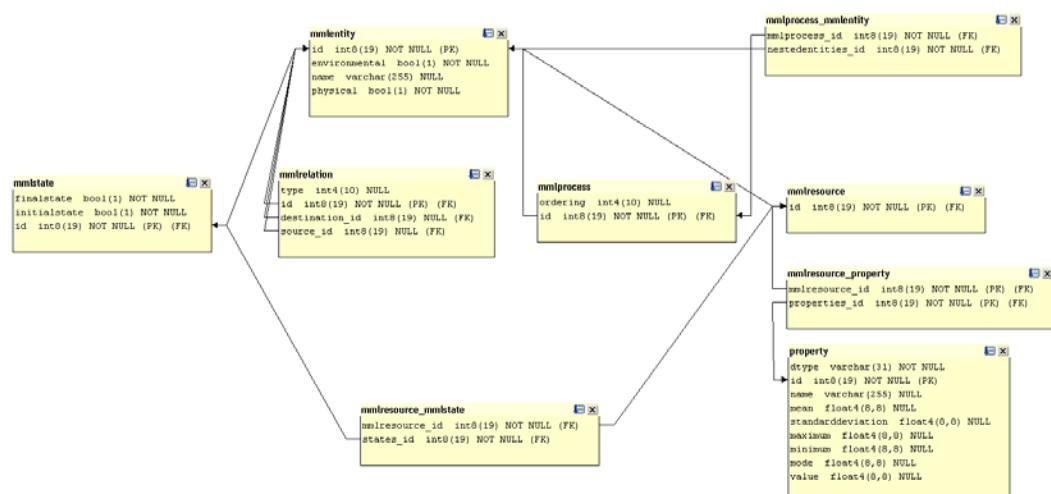
- A unified system model of all aspects of a systems function, structure, and behavior;
- Generic simple methodology that can model ANY natural or artificial system;
- Model expression via both graphics and language that speak to two different channels of the brain improving communication and understanding;
- Built-in abstraction-refinement mechanisms for complexity management; and



- A formality which lends itself to future computer aided applications.

### 3.2 Manufacturing Model Library Database Storage

The manufacturing models developed by the ARL Penn State team were stored in a relational database for easy access, storage and maintainability. The relational database consisted of a PostGres database with the structure shown in Figure 10.



**Figure 10: ARL Penn State Manufacturing Model Library Database**

The full version has been posted to both the DARPA SharePoint and Wiki Pages.

As previously stated, the OPCAT models were saved as .xml representations that provide a definition of the manufacturing process or resource within that process. The .xml files were parsed using a custom Java application developed to convert the .xml file into a format that can be imported into the PostGres database. This same custom application was used to generate Microsoft Excel templates for population of instance data into the MML.

### 3.3 Automated Assembly Sequence Planning

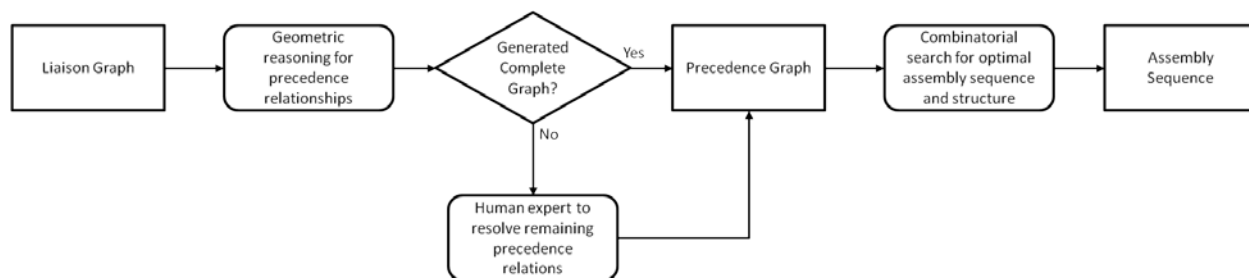
The assembly sequencing has two main functions 1) creating feasible assembly sequences, 2) creating an assembly structure. An assembly can be considered as a combination of several subassemblies, parts and features. Assembly sequencing is a combinatorial problem that deals with different subassemblies or parts. Creating assembly sequences implicitly entails developing an assembly structure. The three steps of assembly sequencing include defining precedence constraints, generating feasible assembly sequences, and choosing one final assembly. The project team implemented a method derived from the two classes of techniques used to solve the assembly-sequencing problem: (a) Geometric Reasoning and (b) Combinatorial Approach.

In the Geometric Reasoning approach, assembly sequencing is interpreted as a reverse disassembly-sequencing problem that involves inferring a sequence of actions that transforms an assembly to an unassembled state - consisting of isolated components (Romney, Godard et al. 1995). The advantage of starting from an assembled state is that it reduces the search space due to inherent constraints (degrees of freedom) on the mobility of individual components. The geometry of the design is used to determine if a part or sub-assembly can be removed without

interfering with other components in the design. This approach can be used to solve the assembly-sequencing problem, however, it is computationally expensive.

The Combinatorial Approach requires the precedence relationships of all the components prior to the development of the graph or tree structures (De Mello and Sanderson 1991). The current state of this approach requires a complex algorithm to cut the liaison graph to generate the precedence relationships or relies on a domain expert. However, once the precedence relationships have been generated, this approach offers more flexibility and reduced computational complexity to generate the assembly sequences and structure. In addition, combinatorial optimization techniques can be applied to quickly search the graphs to determine the assembly sequences.

A hybrid approach would exploit the good properties of each method while making up for the shortfalls. The developed approach receives CAD geometry and an associated liaison graph, performs geometric reasoning to determine the precedence relationships, and performs combinatorial search to derive the assembly structure and sequence. Figure 11 shows the high-level flowchart of the proposed approach.



**Figure 11: Proposed Assembly Sequence Generation Approach.**

Geometric reasoning determines the precedence relationships between the components in the design. We expect that most of assemblies will be decomposable via the geometric reasoning approach and only a few complex designs in a vehicle will need to be interpreted by a human expert. Once the precedence relation is set, the combinatorial approach can complete the solution.

We implemented a Geometric Reasoning approach, a Combinatorial approach, and a hybrid approach that will leverage the positive aspects of each. The Assembly Sequence Generator (ASG), the embodiment of the algorithms, were developed in a custom Java-based application developed by the Penn State College of Engineering in coordination with ARL Penn State.

Automating the assembly planning process helps the designers make decisions, which will result in better assembly planning and hence reduced production time and costs. Of the many costs associated with assembly planning, assembly sequence generation is the major contributor.

Assembly sequencing plays a major role in determining some of the important characteristics such as the difficulty of assembly, in process testing and unit production cost. The role of assembly sequencing in the early phase of product design is fundamental for optimizing not only the manufacturability of the product but also expediting the design process itself. Assembly costs account for 10-30 % of the total cost of many industrial products. Assembly sequence planning

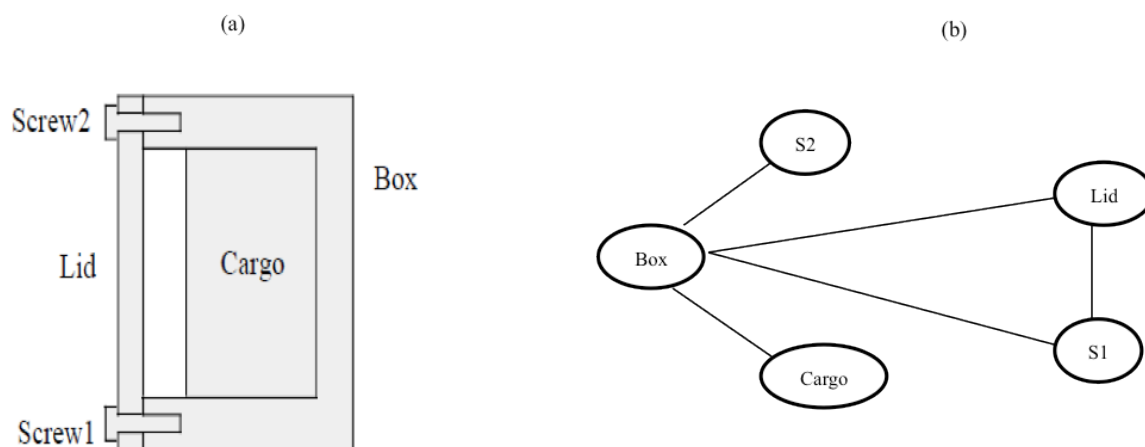
can directly influence the productivity, quality and also the fixed costs which involve machinery and other equipment. Traditionally an experienced industrial engineer generates an assembly sequence for any given product. But there is no guarantee that the optimal assembly sequence hasn't been overlooked. Also for complex products, there will be many possible assembly sequences. It will be a herculean task even for an experienced engineer to generate all feasible assembly sequences as the number of sequences grows exponentially with the number of products. If we can automate the assembly sequence generation, we can guarantee that only the feasible sequences will be generated. The planning of assembly sequences is very time consuming. In order to expedite the assembly sequence generation, reduce the cost and improve the quality, systematic procedures for automating the assembly sequence generation are required. As the assembly becomes increasingly complex, the sequence in which those parts will be assembled will become extremely important.

The process of automatic assembly sequence generation is creating a sequence of parts from the CAD files in which parts can be assembled into a final assembly. For this particular project STEP files were taken as input. It is an ISO standard representation of CAD files and most used format for file exchange. Assembly sequencing can be divided into three stages namely

- 1) Generating Liaison graphs
- 2) Generating Blocking graphs
- 3) Generating Feasible assembly sequences

### 3.3.1 Generation of Liaison Graph

Liaison graph is the representation of contact information between any two parts in a given assembly. Where each node represents a part and the edge connecting them represents the contact between those two parts. A sample liaison graph for a 5-part assembly is shown in Figure 12.



**Figure 12: (a) Assembly of 5 Parts (Wilson, 1992); (b) Liaison Graph**

In the above assembly we can see that 'Lid' is in contact with 'Screw2', 'Screw1' and 'Box', which is represented in Figure 12 (b). Similarly other contacts are defined. This graph can be used to identify subassemblies, which can be assembled in parallel to save time.

### 3.3.2 Generation of Directional Blocking Graph

Directional Blocking Graph (DBG) is the representation of precedence of removal of parts in a given direction. Where each component is represented as a node and there will be a directed edge from one part (A) to another (B), this implies that part B is blocking part A if part A is removed in that direction. For this project we are considering six principal directions  $\pm x$ ,  $\pm y$ ,  $\pm z$ , because the assembly sequencing problem is a NP-hard problem and it would be computationally expensive and infeasible to solve for infinite directions.

A DBG can be derived using a projection method where part (A) which has to be removed is projected in a given direction with respect to other parts (B) and if the projections overlap and if the part A is in front of part B then Part B is blocking Part A. An illustration of this is shown in Figure 13.

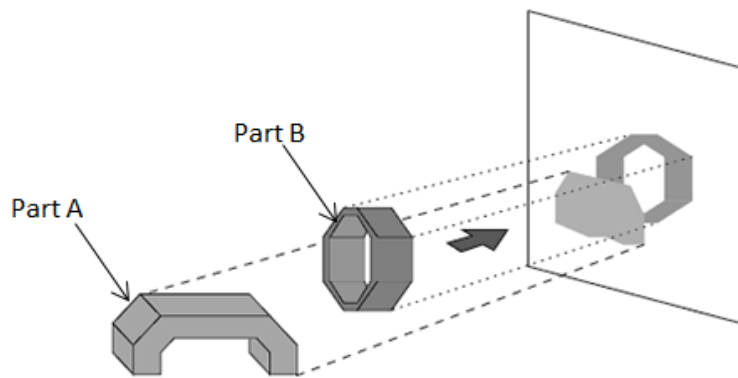


Figure 13: Illustration of Projection Method to Generate the Directional Blocking Graph

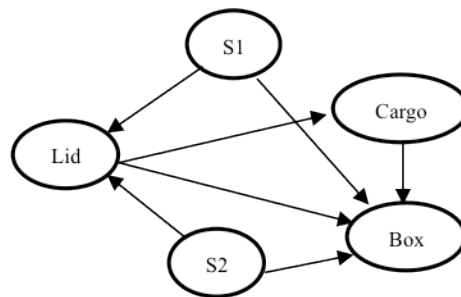
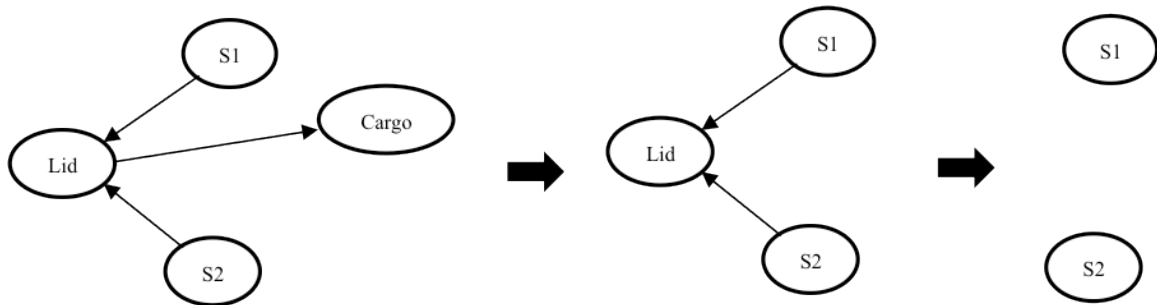


Figure 14: Directional Blocking Graph of Example Assembly in +x Direction

Sample DBGs for assembly in Figure 12(a) is shown in Figure 14. As it can be seen by Figure 12(a) Box is preventing removal of all other parts in +x direction hence in Figure 14 the edges from all other parts is directed towards it. With this rule the complete graph can be generated.

### 3.3.3 Generation of Feasible Assembly Sequences

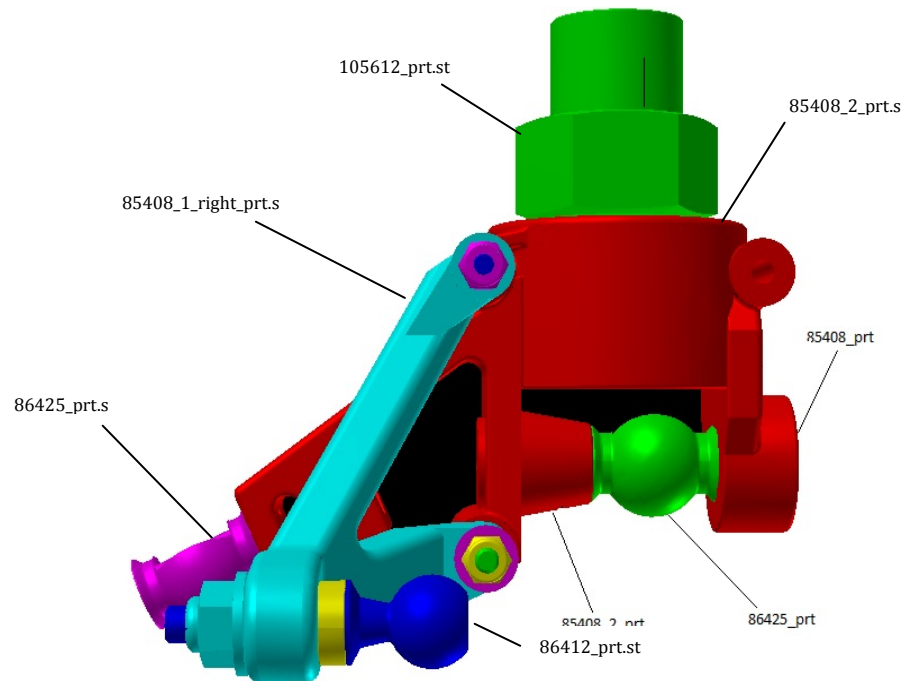
After generating all the DBGs we will first remove the component, which is not being blocked by any other components in any one of the 6 directions. Hence we search for nodes that don't have outgoing edges from them in at least one of the DBG. Then we remove the node from all the DBGs and repeat this rule until there are no other nodes left in the graph having outgoing edges from them. Figure 15 shows this process.



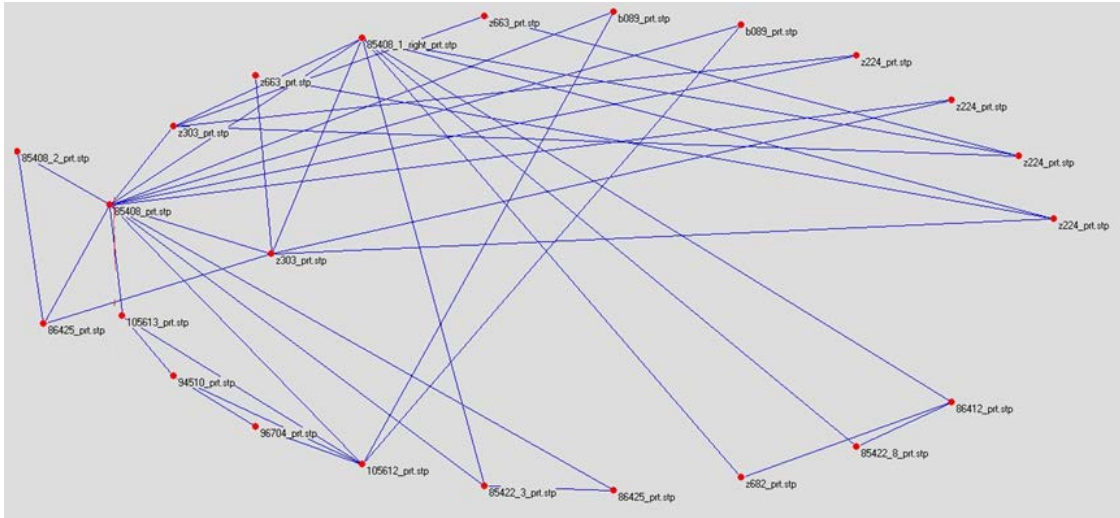
**Figure 15: Stepwise Removal of Parts from the Assembly**

In the above example, Box is removed first because it doesn't have any outgoing edges from it in +x direction. The updated DBG is shown in Figure 15, now we can see that 'Cargo' is not being blocked by any part and hence it can be removed next. We follow this process until all the parts have been removed from the blocking graph. Once we have generated all the feasible disassembly (removal) sequences. Assembly sequences are generated by reversing the disassembly sequences.

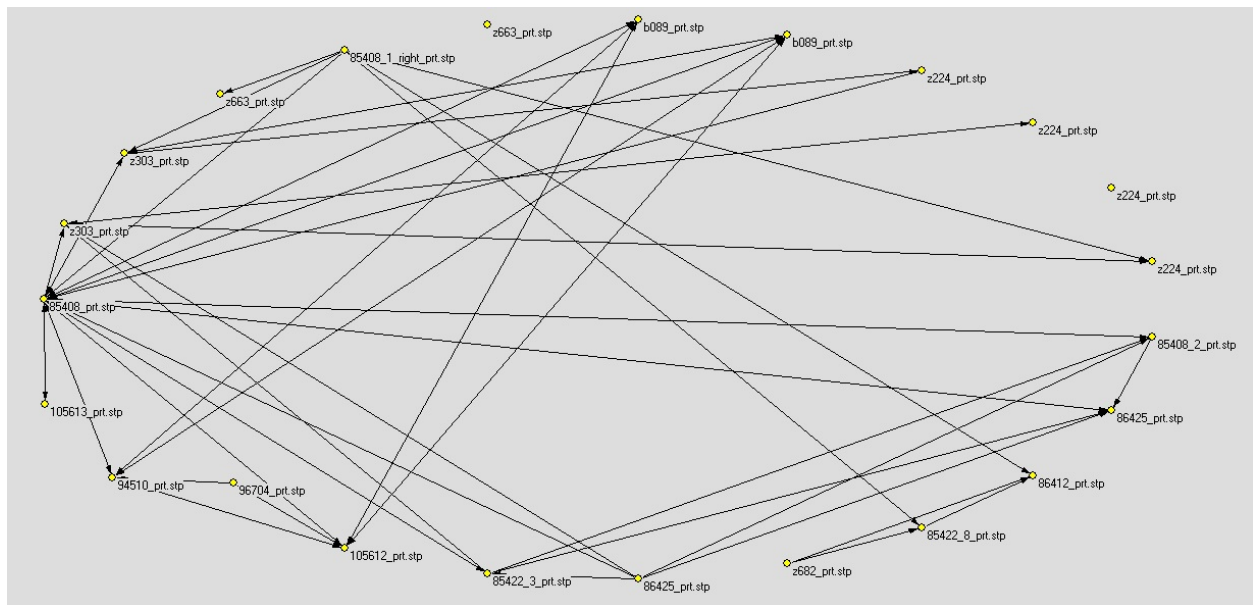
A code was developed to perform these operations and it was tested on several assemblies. Results of one such assembly, containing 23 parts, are discussed below. Figure 16 shows the geometric representation of the example assembly.



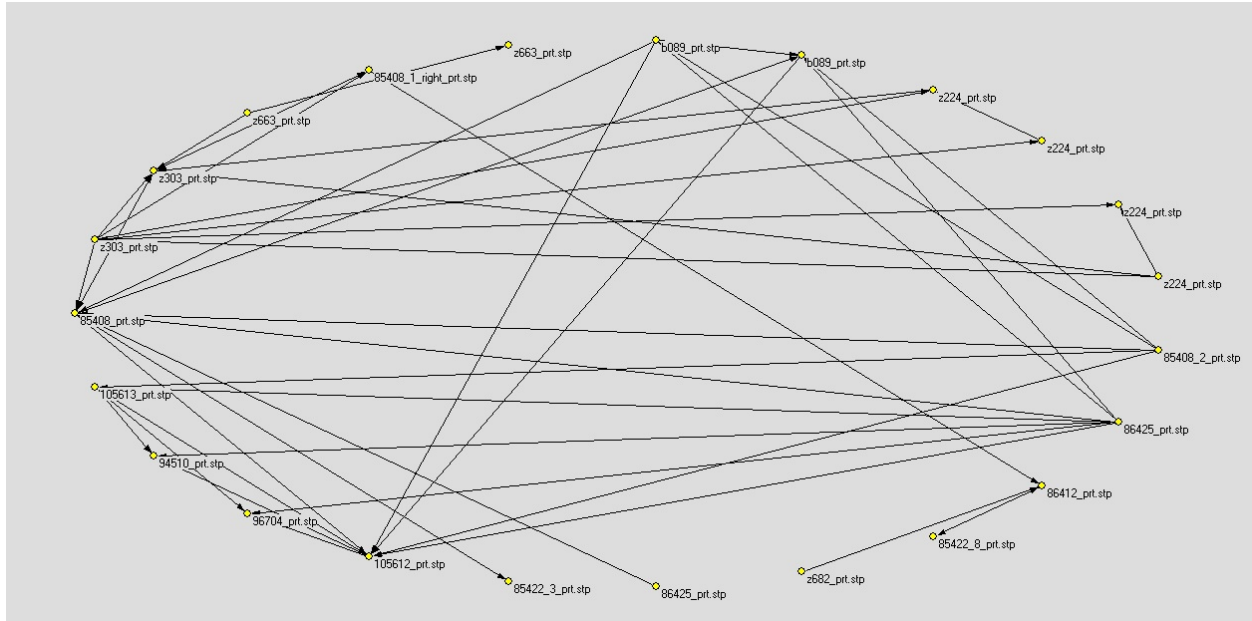
**Figure 16: Example Assembly with 23 Parts**



**Figure 17: Liaison Graph for the 23 Part Example (Front Right Hub Assembly)**



**Figure 18: Directional Blocking Graph +x Direction**



**Figure 19: Directional Blocking Graph +y Direction**

Out of the many feasible assembly sequences generated, one is presented here with operation number and the directions in which the parts have to be assembled.

- |  |                                       |
|--|---------------------------------------|
| 1. z303_prt.stp(-1.0, -0.0, -0.0)          | 12. b089_prt.stp(-0.0, -1.0, -0.0)    |
| 2. z224_prt.stp(-0.0, -0.0, -1.0)          | 13. 105613_prt.stp(-0.0, -1.0, -0.0)  |
| 3. z303_prt.stp(-1.0, -0.0, -0.0)          | 14. 105612_prt.stp(-0.0, -1.0, -0.0)  |
| 4. 85408_prt.stp(-0.0, -0.0, -1.0)         | 15. 94510_prt.stp(-0.0, -1.0, -0.0)   |
| 5. b089_prt.stp(-0.0, 1.0, -0.0)           | 16. 96704_prt.stp(-0.0, -1.0, -0.0)   |
| 6. 85422_3_prt.stp(-0.0, -0.0, -1.0)       | 17. z224_prt.stp(-1.0, -0.0, -0.0)    |
| 7. z224_prt.stp(-0.0, -0.0, -1.0)          | 18. z663_prt.stp(-1.0, -0.0, -0.0)    |
| 8. 85408_1_right_prt.stp(-0.0, -0.0, -1.0) | 19. z682_prt.stp(-1.0, -0.0, -0.0)    |
| 9. 86425_prt.stp(-0.0, -0.0, -1.0)         | 20. 85422_8_prt.stp(-1.0, -0.0, -0.0) |
| 10. 86425_prt.stp(-0.0, -0.0, -1.0)        | 21. 86412_prt.stp(-1.0, -0.0, -0.0)   |
| 11. 85408_2_prt.stp(-0.0, -0.0, -1.0)      | 22. z663_prt.stp(-1.0, -0.0, -0.0)    |
|  | 23. z224_prt.stp(-1.0, -0.0, -0.0)    |

#### 4.0 RESULTS & DISCUSSION

This section presents the detailed manufacturing and resource models developed in this project. Table 1 presents the processes and sub-processes modeled and included in the MML.

**Table 1: Detailed Manufacturing Model Listing**

Process Category	Process
Casting	Non-Cored and Cored Green Sand Casting
Plate/Sheet Cutting	Laser, Oxy fuel, Water jet, and Plasma Cutting
Wire Harness Assembly	Harness Assembly
	Junction Box Assembly
	Instrument Panel Assembly
Inorganic Coatings	Chrome Plating, Zinc Plating, Black Oxide Plating, Phosphate Plating
Organic Coatings	Pre-coat processing, Powder Prime, Spray Prime, Powder Topcoat, Spray Topcoat
Direct Digital Manufacturing	Power Feed Process
	Powder Bed Process
Welding	Shielded-Metal Arc Welding (Stick), GMAW (TIG), GMAW (MIG), Flux-Cored Arc Welding, Submerged Arc Welding
Forming	Press Forming
	Roll Forming
Machining	Milling, Turning, Drilling, Wire EDM, etc.
Material Handling	Crane, Fork Truck, Pallet Jack, and Manual Moving
Assembly	
Dimensional Control (A&I)	



## **4.1 Welding**

Welding is the process of joining two metallic parts together. There are several aspects to welding that should be taken into consideration in a welding manufacturing model. These include specific welding processes, allowable joining materials, joint definition, welding procedure and cost modeling. As described earlier, the resources used in the welding process are implicitly defined within the above categories and have a significant effect on the quality, time and cost of the welding operation.

### **4.1.1 Welding Processes/Procedures**

In general, welding is divided into several high level processes with electrode (gas metal arc), solid state (friction stir), and laser-hybrid welding being the most relevant to medium to heavy welding required for a military ground vehicle. The project team focused on electrode type welding processes, specifically gas metal arc welding (GMAW).

The GMAW process is used to join materials using various joint types and is a very flexible process using widely available welding resources. These resources include power supplies and wire feeders along with more advance (and less widely available) welding robots and robotic welding cells.

The primary constraints/attributes of the process are materials and joint definition.

### **4.1.2 Materials**

When two or more pieces of metal are being welded together there are many things to consider when trying to answer the question of whether it is feasible. If the two metal alloys are the same, then it is relatively simple depending on the alloy choice. The filler material must also match the base component metal alloy. The base material alloy also affects the welding process in that certain alloys require pre-heating the base material to a predefined temperature prior to starting the weld and also may include interpass temperature values that cannot be exceeded (heat input limitations).

The base materials dictate the amount of heat that is input into the weld to perform the joint type specified by the designer and to minimize the distortion of the final assembly during and after the weld is performed. Softer alloys such as aluminum can tolerate less heat input to maintain tolerances and high quality welds. Whereas, steel and more advanced alloys of aluminum are less affected by the heat input, but heat input and distortion is still an issue.

If the base component materials are not the same, then it may still be possible to perform the weld, but the degree of difficulty (feasibility, cost and time) is increased and could result in an infeasible joint type. Oftentimes, welds of this type are classified as cladding or additive manufacturing to capitalize on characteristics of two alloys rather than relying solely on the mechanical properties of a single alloy.

Although welding of different base materials is an accepted process, for the purposes of this project, the team did not develop detailed manufacturing models for these types of welds.

### 4.1.3 Joint Definition

There are many types of weld joints and each has specific mechanical properties as well as manufacturing implications. Further characterization of the joint type is given by defining the weld of the joint type, i.e. full or partial penetration weld. Figure 20 shows the standard welding joint types.

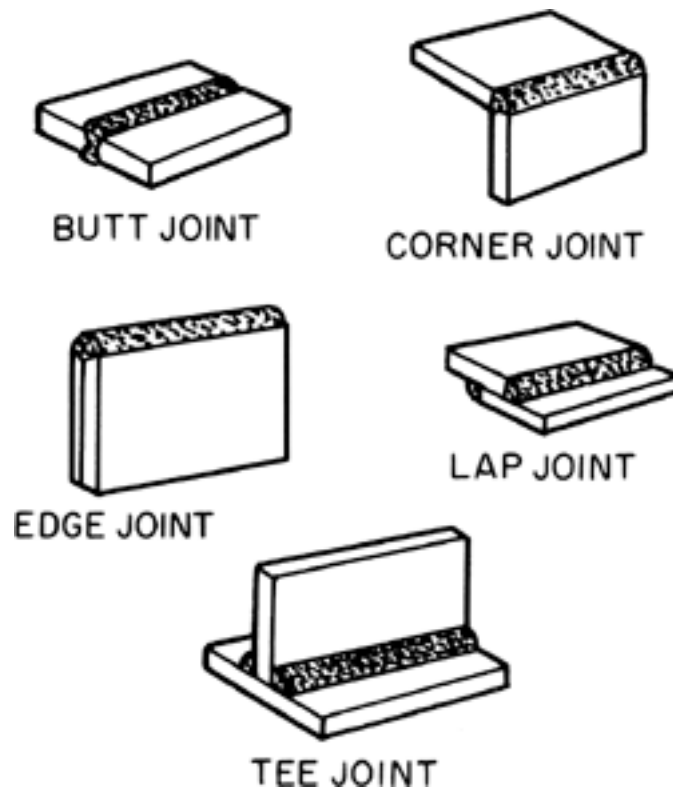


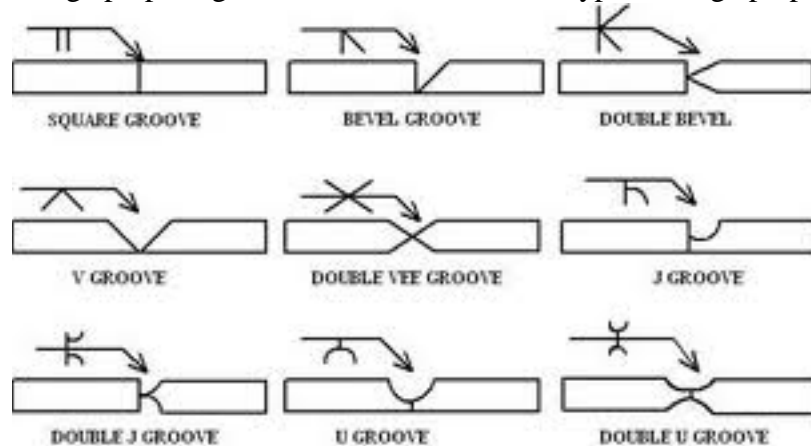
Figure 20: Standard Welding Joint Types

Each of the standard welding joints form variations that affect the feasibility, cost and time of a given weld joint. Depending on the joint type and weld type (full or partial penetration) the edges of the pieces of material being welded may have to be prepared (edge prep). In addition, the orientation of the assembly in space as the welder is performing the weld affects the feasibility, time and cost of the welding operation.

Full penetration welds are described as welds that fully penetrate both of the base materials through the thickness of the base material. These types of welds are most common on Butt, Corner, Lap and Tee joints. Full penetration welds are more structurally sound, but required advanced inspection techniques (x-ray, magnetic particle, etc.) to ensure that the weld meets the specifications. Partial penetration welds are welds that don't fully penetrate the base material and are used for less structurally rigorous applications and a simple visual inspection is usually required post welding.

Edge preparation entails cutting the edges of the components at some angle to aid in full penetration welds. This preparation step can be performed on plate cutting resources or by being machined after being cut out in a plate cutting process. Therefore, welding process

manufacturing models link to plate and sheet cutting processes as well as machining processes to achieve the proper edge prep. Figure 21 shows the different types of edge preparation.



**Figure 21: Edge Preparation Types**

Orientation of the weld operation further characterizes the weld. There are four general types of orientations used in welding: down hand, flat, vertical, and overhead. Down hand and flat are the most desirable orientations because they are easier to set up and control the weld. Vertical and overhead are more difficult and require additional training, take more time to set up and perform, and are more prone to defects.

#### **4.1.4 Welding Cost Model**

The project team developed a cost model for welding to automatically determine the cost and time of a specified joint using only the information provided to the iFAB Foundry performer team. Figure 23 shows the cost model developed by the ARL PSU team and delivered to the iFAB Foundry performer for use in the AVM MML.

Inputs to the model		
(Items that are limited are in a drop down list)		
<b>Enter Weld Design Data</b>		
Material to be Welded	Plain Carbon Steel	choose
*Base Metal Thickness (gauge/ in.) (for joining two different thicknesses choose smallest thickness)	1/4"	choose
Joint Length	2.75	ft
Weld Length (% of Joint Length if intermittent weld) (between 50 and 100%)	100	%
Type of Joint	Tee	choose
Sides of Joint Welded	Single	choose
* If thickness is not available on Process Parameter spreadsheet, then it is outside the current capability limits.		
<b>Enter Appropriate Cost Factors Based on Material and Thickness and Joint (SEE PROCESS PARAMETER SPREADSHEET)</b>		
Cost of Material per ft of Weld	8.388255286	
Labor Hours per ft of Weld	0.154384218	
<b>COST OF WELD</b>	<b>\$23.07</b>	
<b>Process Hours</b>	<b>0.42</b>	
<b>Other Potential Cost Factors (to be accounted for later... after discussion with source and list of expect</b>		
Location of Weld Operations	indoors	
Piece movement / Set Up / Removal	assisted manual	
Piece / Tack Up / Cleaning / Assembly	1000-2000mm	
Part Size	both accessible	
Accessibility of joint faces	Oxycutting	
Joint Preparation		
Preheat required		Time and Temperature
Required Joint Penetration		Assume 100% for first round
Weld Quality	butt single sided, unbacked	Assume best for first round
Weld Type	V	
Groove Profile		
Post Weld Heat Treat / Stress Relieving		Assume not required for first round
NDE Costs		Add an estimate based on a drop down list
Shape of Material to be Welded (this model only assumes plate)		
Root Opening / Joint Clearance (in) - not used in this model		in
Type of Weld (this model only using fillet for all but butt and edge joints, and square for butt joint, no joint prep)		choose
Weld Position (not used in this model)		choose
Reinforced (added metal bead) Not used in this model		
Weld Inspection requirement (not used in this model)		

Figure 22: Welding Process and Cost Model

Additional information used in the development of the cost model is provided in the appendix.

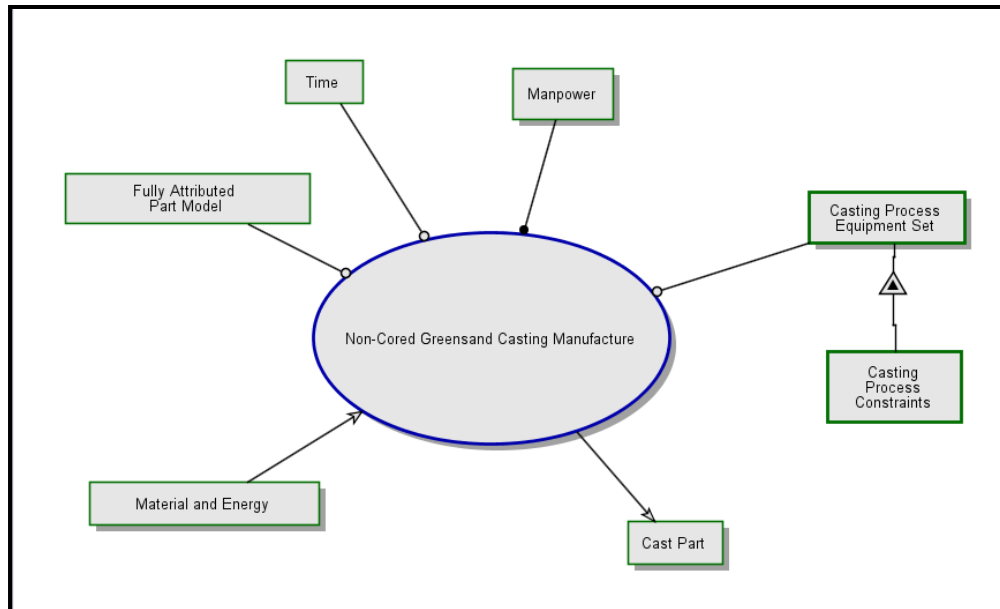
## 4.2 Casting

The project team developed manufacturing models for Cored and Non-Cored Green sand casting. Details of the two processes are presented in the following sections.

### 4.2.1 Non-Cored Green Sand Casting

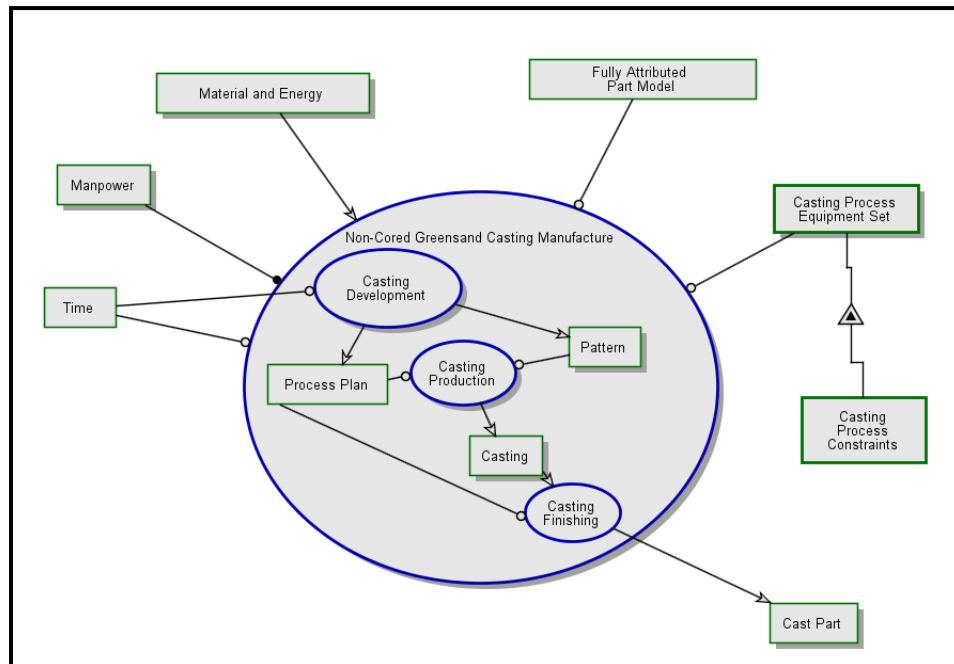
Below is an example process model developed using OPCAT for a Non-Cored Greensand Casting process. Many of the figures show a unique sub-process to the higher-level Non-Cored Greensand Casting process, thus illustrating the hierarchical aspect of the modeling methodology.

Figure 23 shows the top level Non-Cored Greensand Casting process along with several relations and links that are clearly described in Appendix A, a glossary of OPM process model elements.



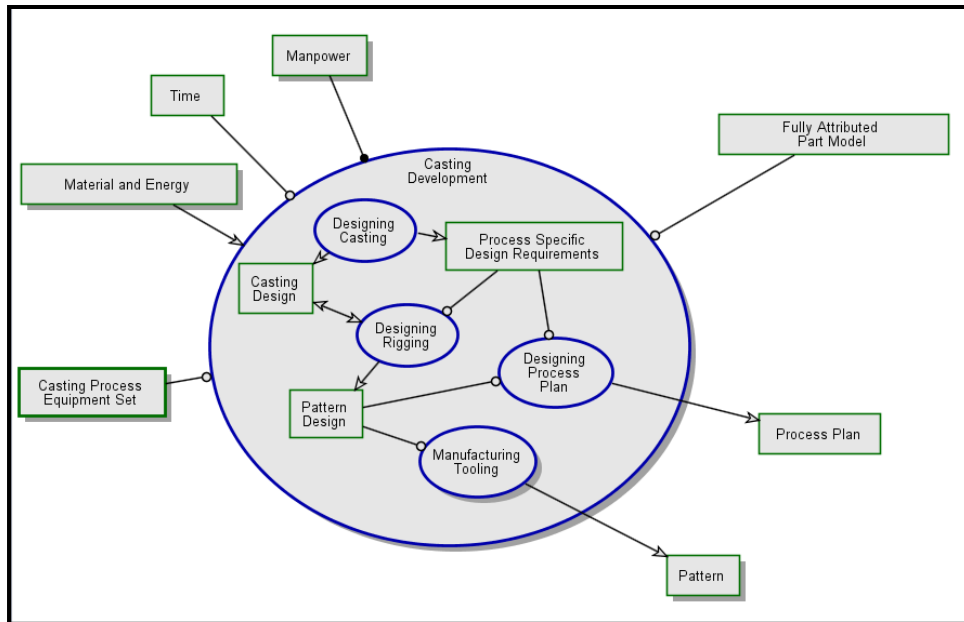
**Figure 23: Non-Cored Greensand Casting Manufacturing Process**

Figure 24 demonstrates a unique characteristic in OPCAT called “in-zooming”, which allows for greater levels of process detail input for a particular process. In this case, you can see that Non-Cored Greensand Casting process consists of a Casting Development process, which produces a process plan and a pattern. The process plan and pattern are inputs to the Casting Production process. Casting Production makes the casting, which is the input into the Casting Finishing process.



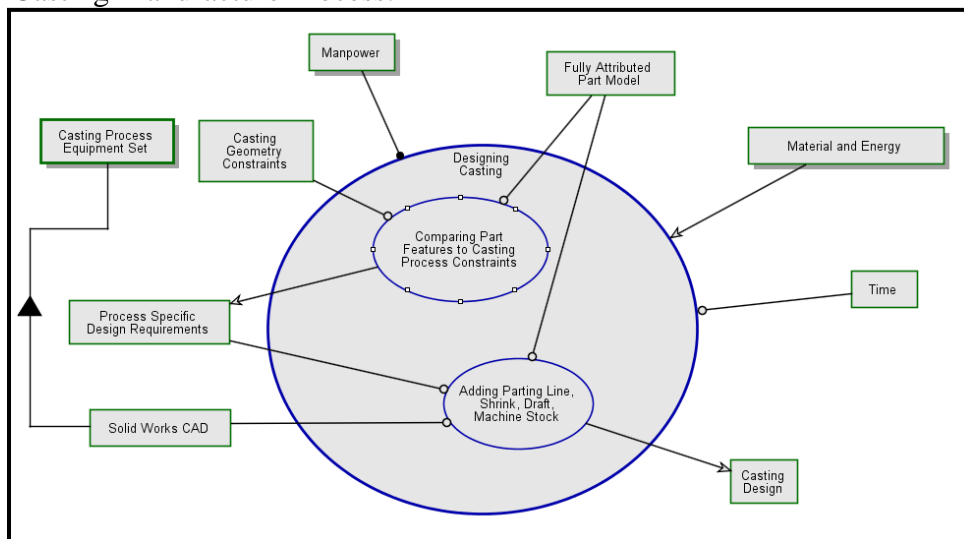
**Figure 24: Non-Cored Greensand Casting Manufacturing Process (Detailed)**

Further in-zooming shows the details of the Casting Development process (Figure 25)

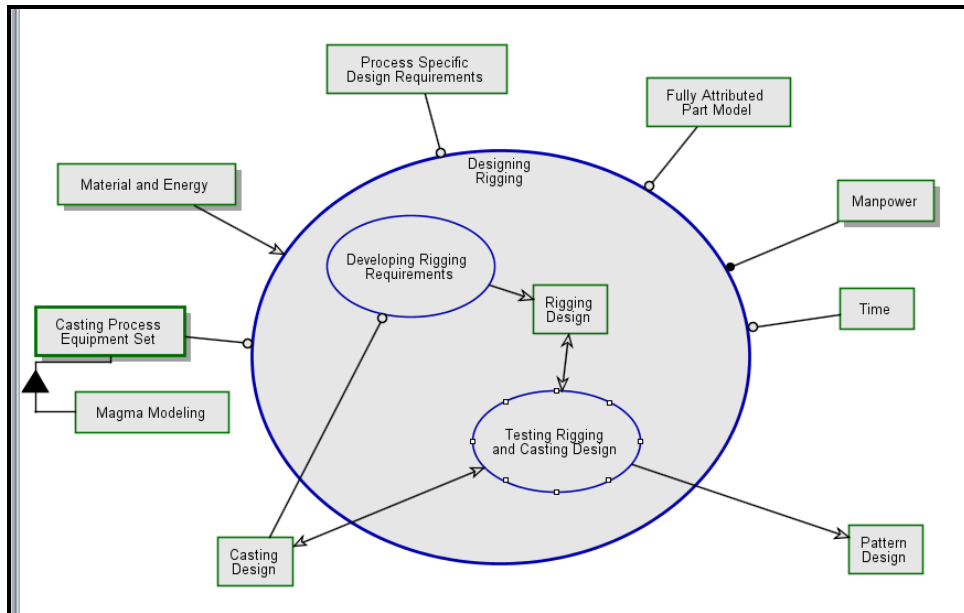


**Figure 25: Casting Development Process**

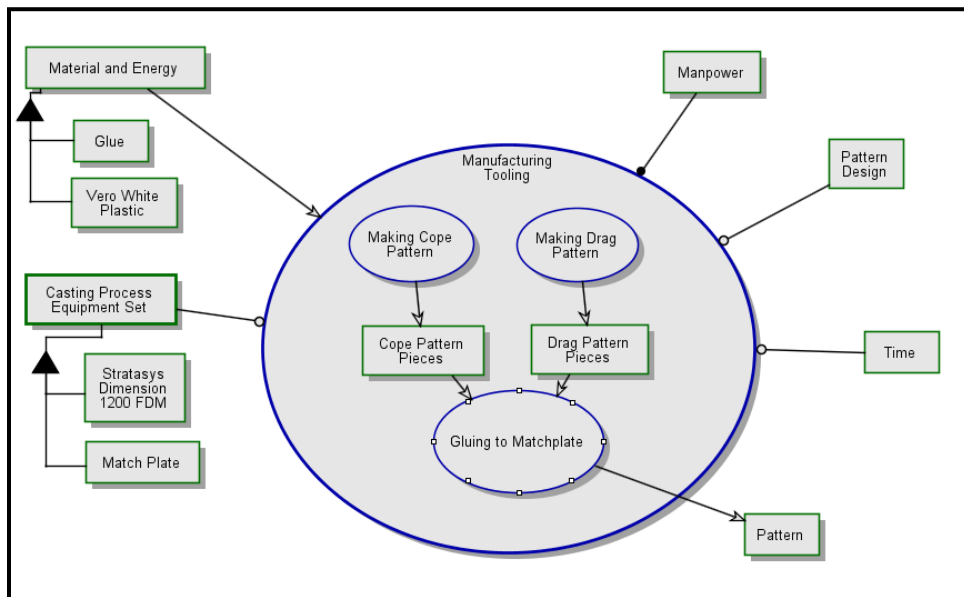
Figure 26-Figure 35 continue to in-zoom to more detailed sub-processes under the Non-Cored Greensand Casting Manufacture Process.



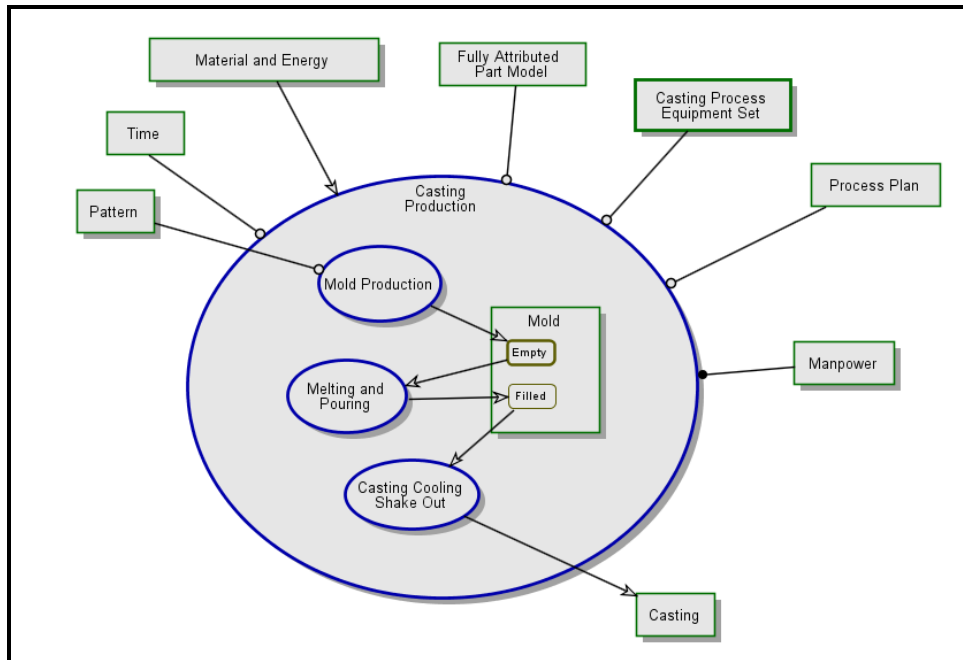
**Figure 26: Designing Casting Process**



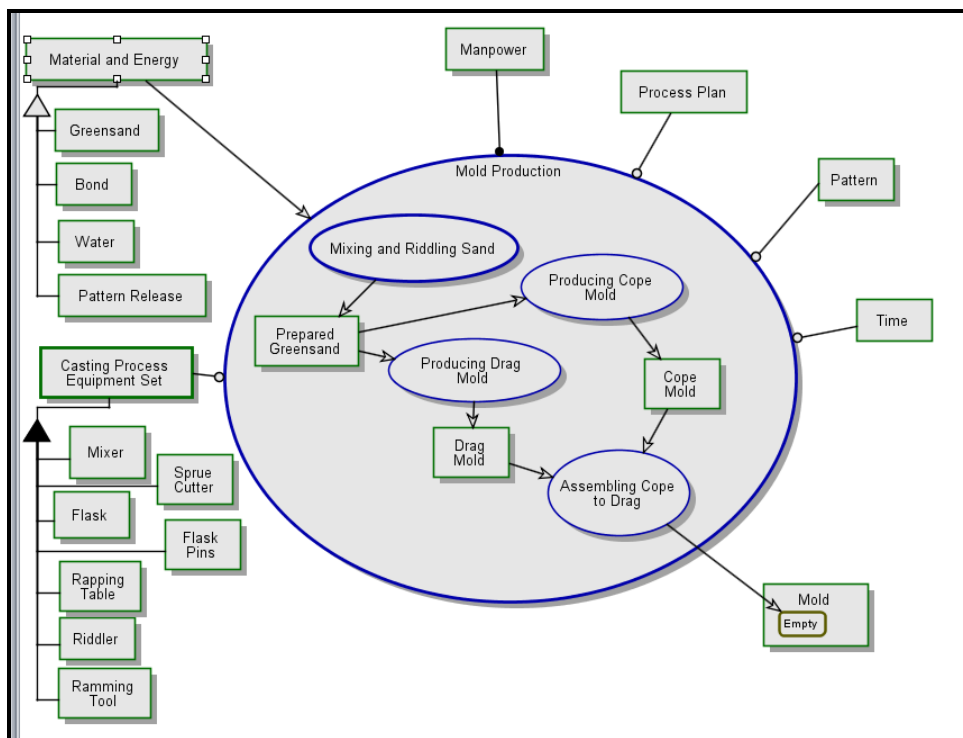
**Figure 27: Designing Rigging Process**



**Figure 28: Manufacturing Tooling Process**

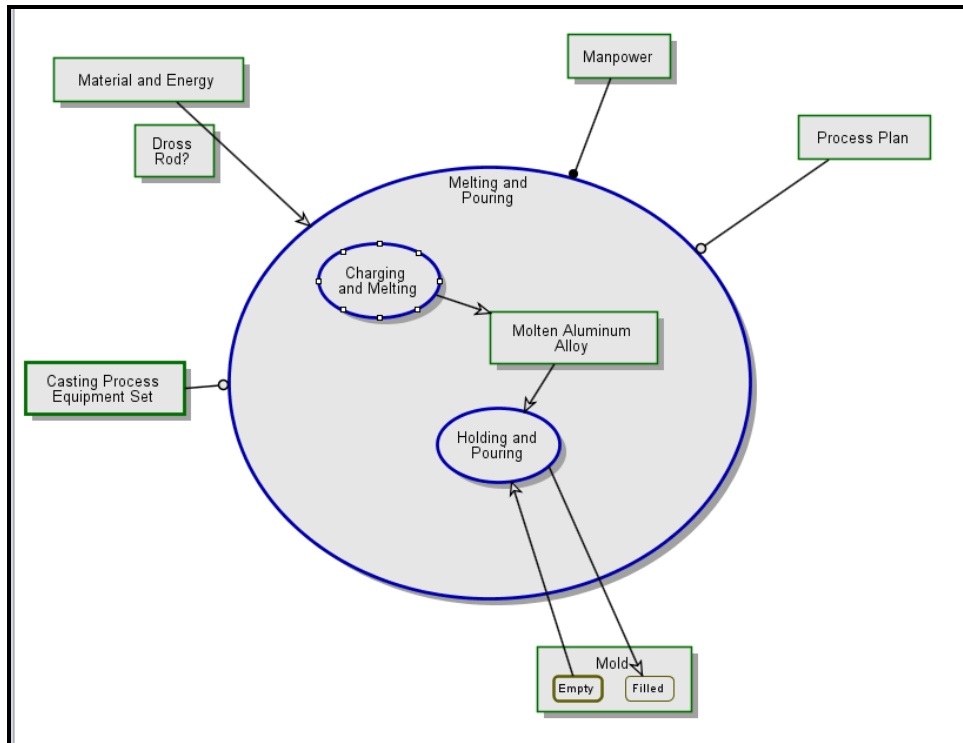


**Figure 29: Casting Production Process**

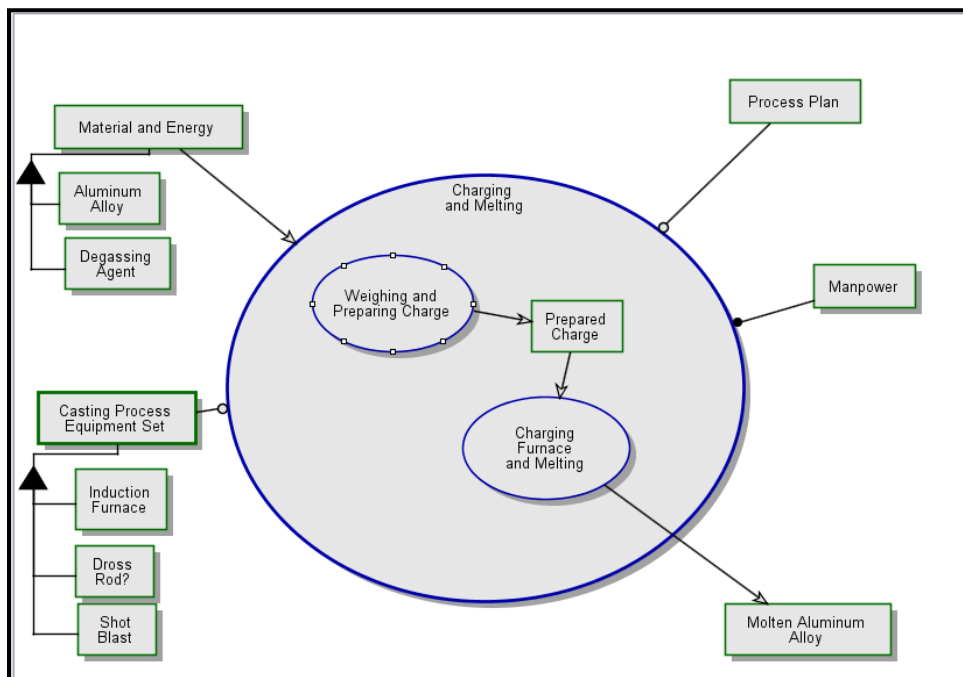


**Figure 30: Mold Production Process**

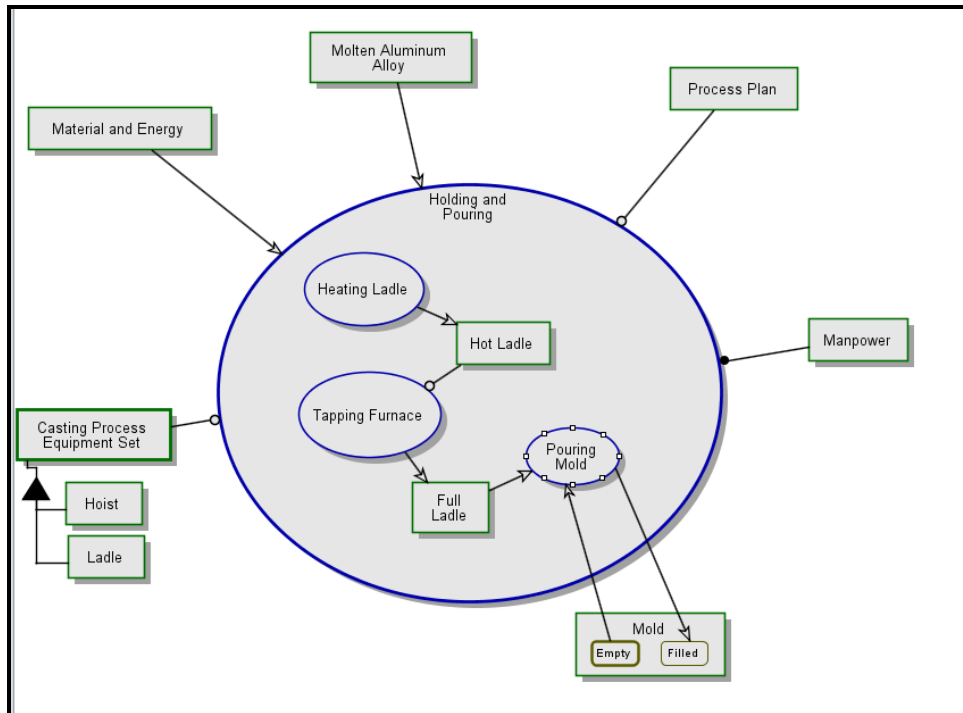




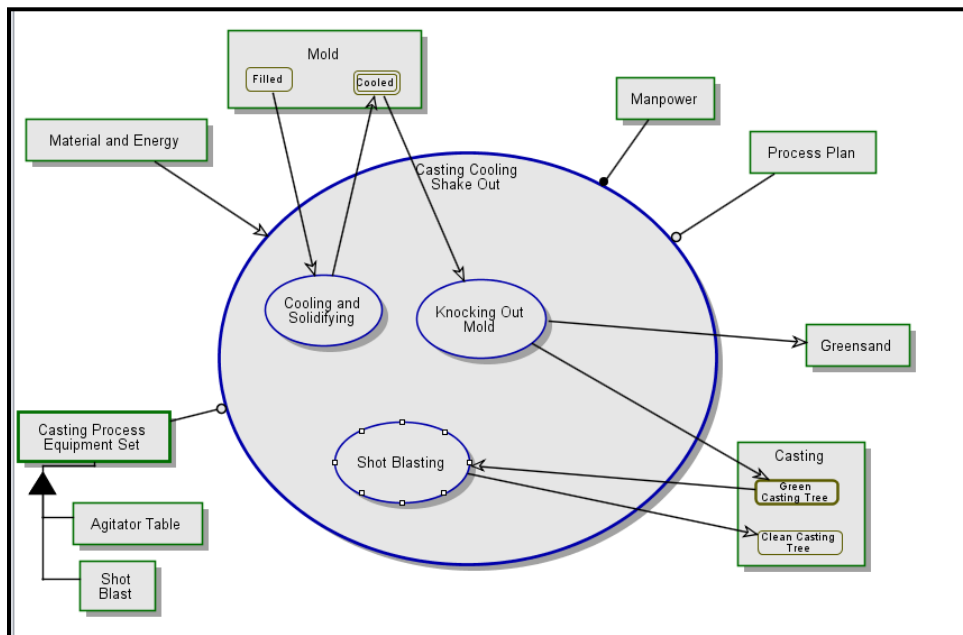
**Figure 31: Melting and Pouring Process**



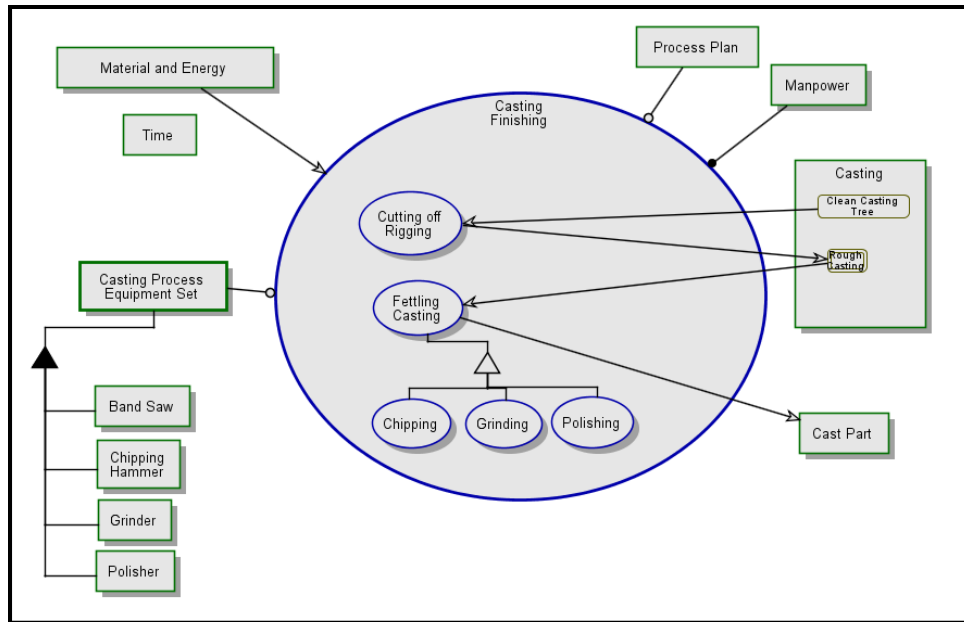
**Figure 32: Charging and Melting Process**



**Figure 33: Holding and Pouring Process**

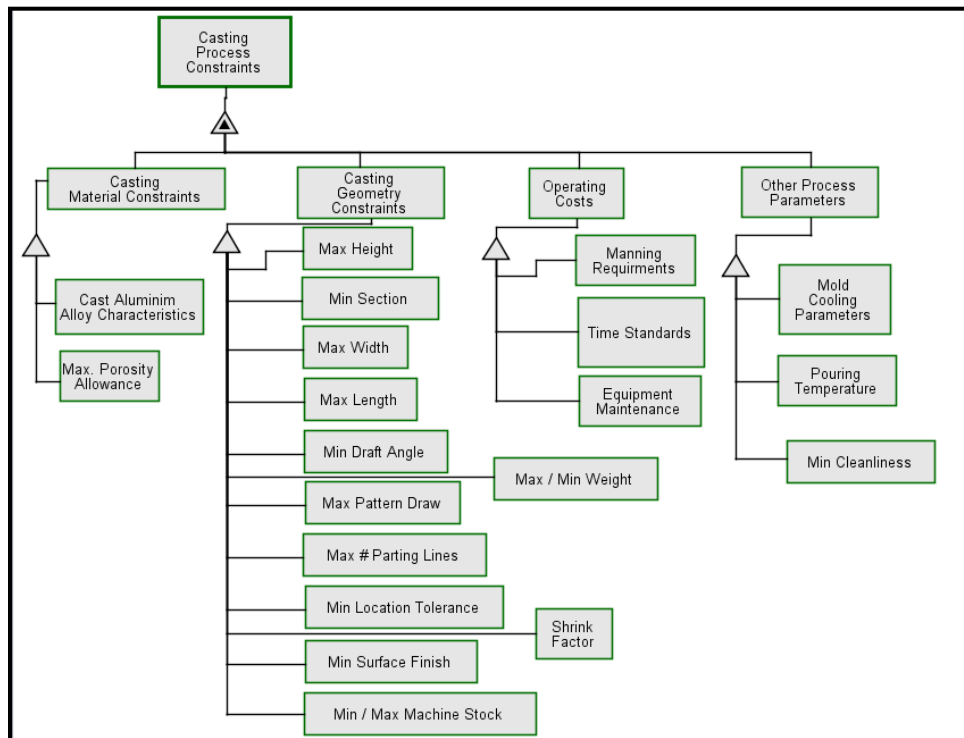


**Figure 34: Casting Cooling and Shake Out Process**



**Figure 35: Casting Finishing Process**

The OPM process models also allow for the definition of process constraints, as shown in Figure 36.



**Figure 36: Casting Process Constraints**

In addition, OPM enables the definition of equipment sets that are required to complete the process (Figure 37-Figure 38). While the equipment objects in the model can get down to the instance data for specific resource types, our process modeling approach will specify resources

of a specific type, and we will rely on the agent system to interface with the MML for the selection of the specific resource instance that satisfies that resource type.

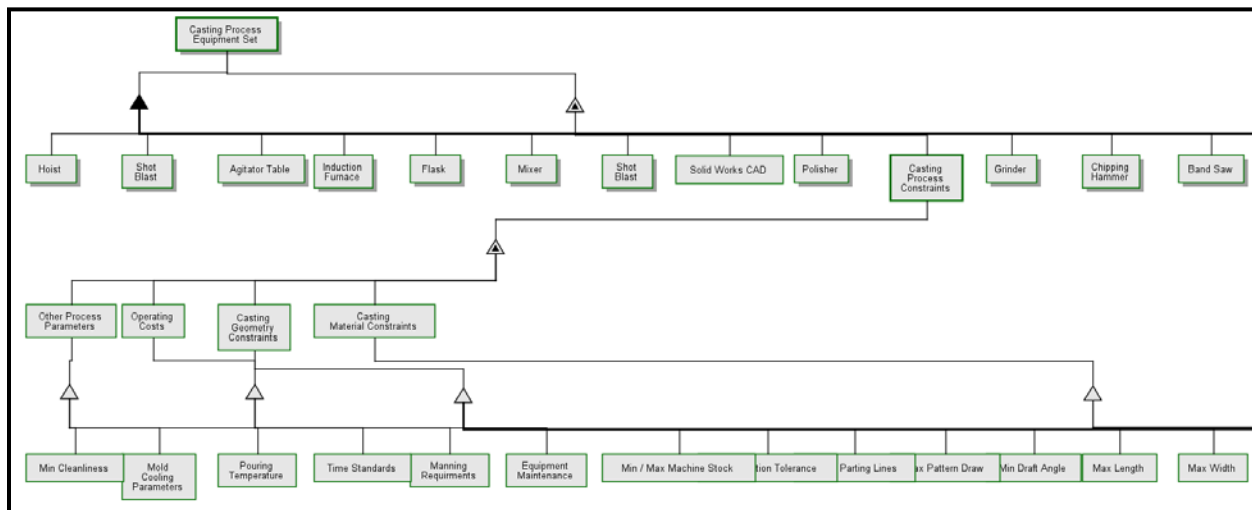


Figure 37: Casting Process Equipment Set

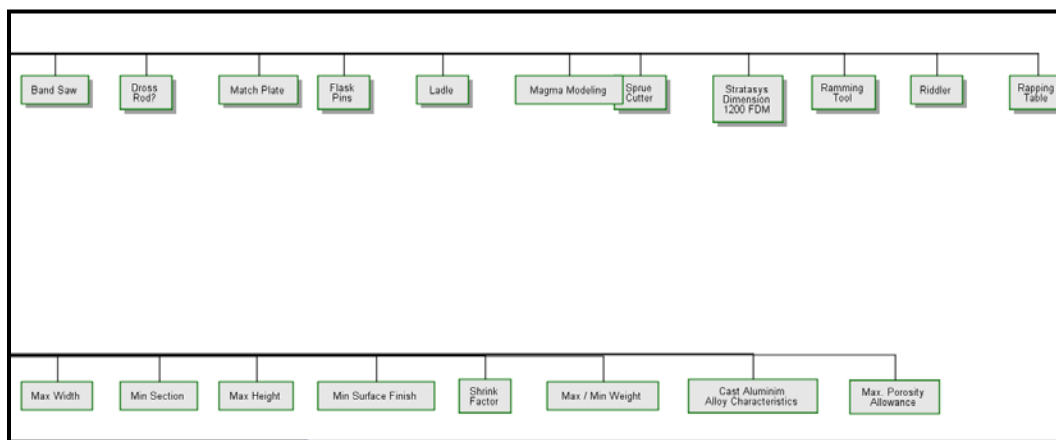
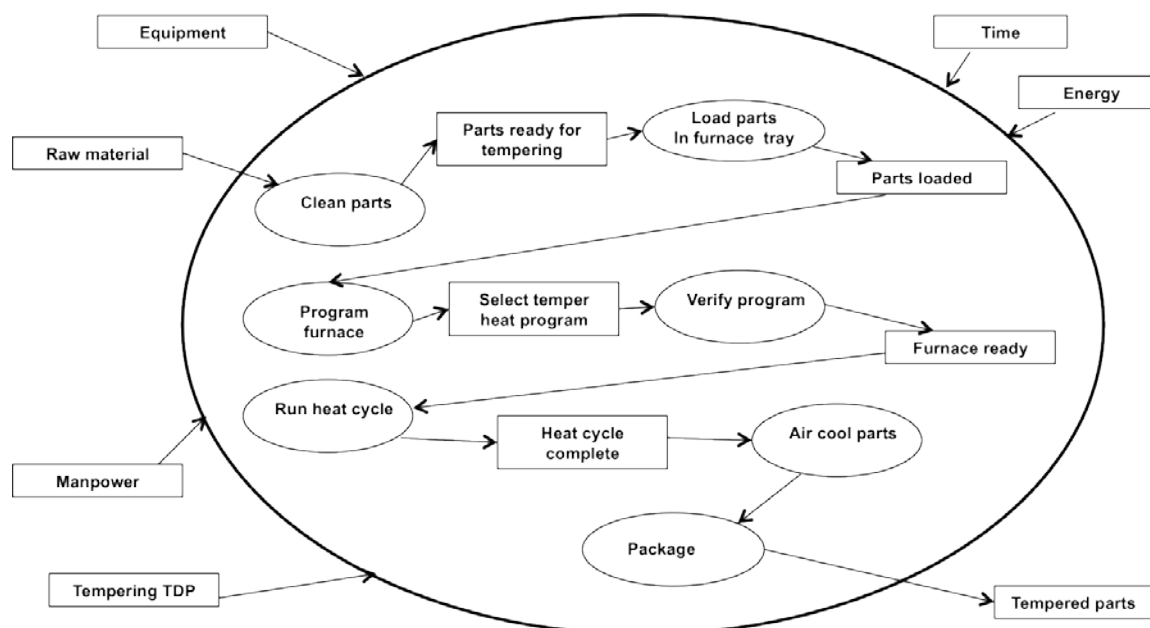


Figure 38: Casting Process Equipment Set (Cont.)

### 4.3 Heat Treating Processes

Figure 39 shows the general process model for heat treating or tempering process. Heat treating is a seven step process that requires a programmable heating oven and an operator. This process may or may not be a batch process depending on the size and type of oven.



**Figure 39: Heat Treatment Process Model.**

In addition to populating the MML with the general heat treat process model, we also developed a mapping of the most commonly cast Aluminum and Carbon Steel alloys, temper and tensile strength requirements, heat treat processes, and furnace resources required for those processes. This information, summarized in Tables 2-7, was also included in the MML and could be used to support manufacturability assessment, process planning, and time/cost estimation for castings.

**Table 2: Available Aluminum alloys and temper treatments**

ANSI Alloy Type	Temper*	Tensile strength (min) [ksi] ([MPa])	Yield strength (min) [ksi] ([MPa])	Elongation in 2 in [%]
319	F	23.0 (159)	13.0 (90)	1.5
	T6	31.0 (214)	20.0 (138)	1.5
355	T6	32 (221)	20.0 (138)	2.0
356	T6	30.0 (207)	20.0 (138)	3.0
512	F	17.0 (117)	10.0 (69)	N/A

\*T6 refers to heat treated, and F refers to as-cast (i.e., no heat treatment)

Based on the Aluminum alloys found in Table 2, we defined the heat treatment requirements for T6 and captured these in the MML. These are summarized in Table 3.

**Table 3: Aluminum Alloy T6 Temper Requirements**

Step	Furnace Designation	Temperature (°F)	Time (hr)
Solutionize	S	1000	12
Water Quench	Q	N/A	0.33
Age	A	310	8

The most common Steel castable alloys, their tensile requirements and grade stability, and requirements definitions are displayed in Table 4 and Table 5.

**Table 4: Common Steel Alloys, Tensile Requirements/Grade Suitability, and Heat Treatment Designators\***

Class	65/ 35	70/ 36	80/ 40	80/ 50	90/ 60	105/ 85	115/9 5	130/1 15	135/1 25	150/1 35	160/1 45
1020	N	N									
1025	N	N									
1030	N	N	N								
1040	N	N	N	Q,T							
1045			N	Q,T	Q,T	Q,T					
4130			N	Q,T	Q,T	Q,T	Q,T	Q,T	Q,T		
4140				Q,T	Q,T	Q,T	Q,T	Q,T	Q,T	Q,T	
4330				Q,T	Q,T	Q,T	Q,T	Q,T	Q,T	Q,T	Q,T
4340					Q,T	Q,T	Q,T	Q,T	Q,T	Q,T	
8620	N	N	N	Q,T	Q,T	Q,T					
8625		N	N	Q,T	Q,T	Q,T	Q,T	Q,T			
8630		N	N	Q,T	Q,T	Q,T	Q,T	Q,T	Q,T		

\* N (Normalize), Q,T (Quench and Temper)

**Table 5: Steel Tensile Requirements Definition**

Class	65/ 35	70/ 36	80/ 40	80/ 50	90/ 60	105/8 5	115/9 5	130/1 15	135/1 25	150/ 135	160/ 145
Tensile ksi (MPa)	65 (450)	70 (485)	80 (550)	80 (550)	90 (620)	105 (725)	115 (795)	130 (895)	135 (930)	150 (1035)	210 (1450)
Yield ksi (MPa)	35 (240)	36 (250)	40 (275)	50 (345)	60 (415)	85 (585)	95 (655)	115 (795)	125 (860)	135 (930)	145 (1000)
El. in 2 in or 50 mm min, %	24	22	18	22	18	17	14	11	9	7	6
Reduction of area, %	35	30	30	35	35	35	30	25	22	18	12

We defined heat treatment requirements for Normalizing (N) and Quench & Temper (Q,T) heat treatment of steel casting and captured these in the MML. These are summarized in Table 6.

**Table 6: Steel Alloy Heat Treatment Details**

Heat Treatment	Step	Furnace Designation	Temperature	Time (hr)
Normalize	High Temp	N	1700°	6
	Air Cool	N/A	N/A	2
Quench & Temper	High Temp	AQ	1700°	6
	Quench	N/A	N/A	0.33
	Temper	T	1100°	4

Finally, we developed resource models for several representative furnaces that would be used in the heat treatment process steps defined in Table 2 and Table 6 and included these in the MML. These heat treatment furnace resources are summarized in Table 7.

**Table 7: Furnace Resources Modeled in MML**

Furnace #	Furnace Use *	Power	Work Length (in)	Work Depth (in)	Work Diameter (in)	Work Height (in)	Temp Max	Capacity (lb)
1	T,S,A	Electric			12	15	1200	
2	T,S	Electric			37	60	1400	
3	N,S,T	Electric	216	114		90	1700	
4	T,S	Electric	36		27	36	1400	1000
5	T,S	Electric			14	16	1150	
6	O	Electric	42	36		24	1000	
7	T,S	Electric			22	48	1250	
8	O	Electric	36	20		24	1700	
9	T,S	Electric			22	36	1250	
10	T,S	Electric	36	36		24	1250	
11	T,S	Electric			21.75	26	1400	
12	T,S	Electric			50	120	1500	
13	O							
14	O	Electric	48	30		10	2500	
16	T,S	Electric			50	84	1400	
17	T,S	Electric	384	114		96	1400	6000
18	N	Electric	144	72		48	2000	5000
19	S,Q, A	Electric	48	48		48	1200	100
20	O				48	144	1800	6000
21	T,S	Gas			48	144	1400	10000
22	N,AQ	Gas	48	36		30	1750	
23	N,AQ	Gas	36	24		24	1750	1200
24	T,S,A	Electric	48	36		30	1400	3000
25	T,S,A	Electric	48	36		30	1400	3000
26	T, S,A	Electric	48	36		30	1400	3000

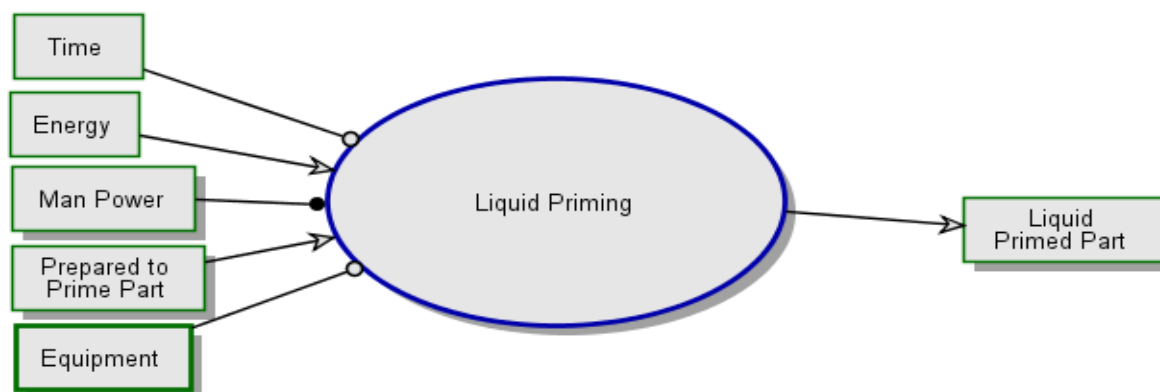
\* T (tempering or stress relieving of steel), S(solutionizing of aluminum), A (aging of aluminum), N (normalizing or annealing of steel), AQ (austenitizing and quenching of steel), O (Other)

#### 4.4 Organic Coatings

Organic coatings manufacturing processes include painting in both liquid and powder forms. The following sections describe the developed organic coatings manufacturing models.

##### 4.4.1 Liquid Priming

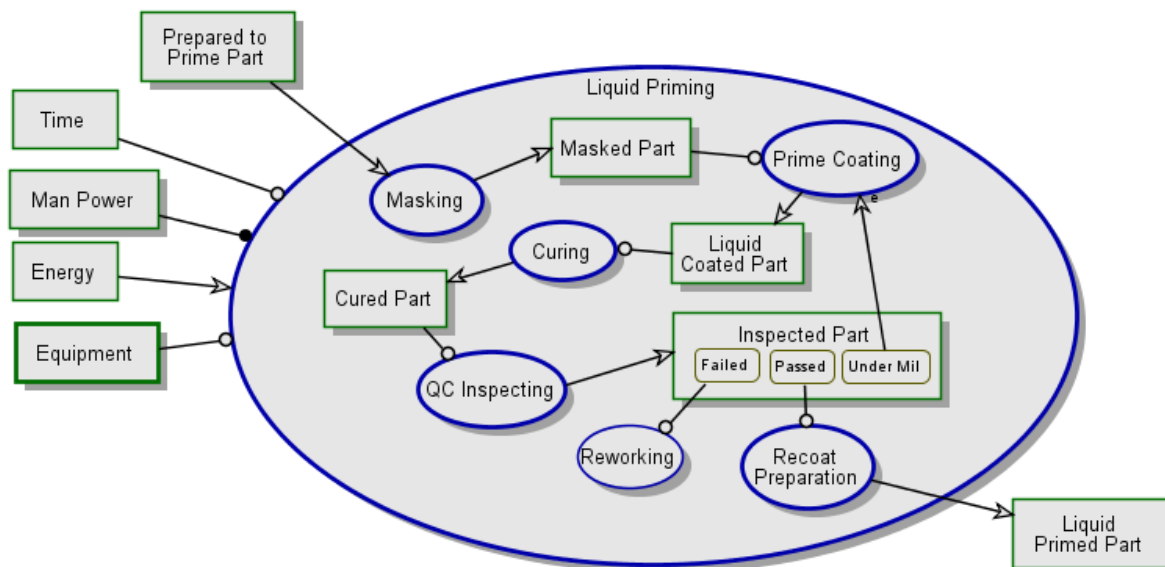
Figure 40 shows the top-level process model for the liquid priming process. Liquid priming requires time and equipment. Also, the process consumes energy and a prepared to prime part to yield a liquid primed part.



**Figure 40: Liquid Priming Process Model**

The in-zoomed liquid priming process model is shown in Figure 41. The in-zoomed model illustrates the sub-processes involved in the liquid priming process. Every part that begins the liquid priming process follows the same four initial sub-processes, which are masking, prime coating, curing and QC inspecting.

The QC inspecting sub-process yields an inspected part with one of the three possible states: failed, passed or under mil. The state of the inspected part determines the path that the part follows from this point. A failed inspected part gets reworked, a passed inspected part goes to the recoat preparation process while an under mil inspected part goes back to the prime coating process.

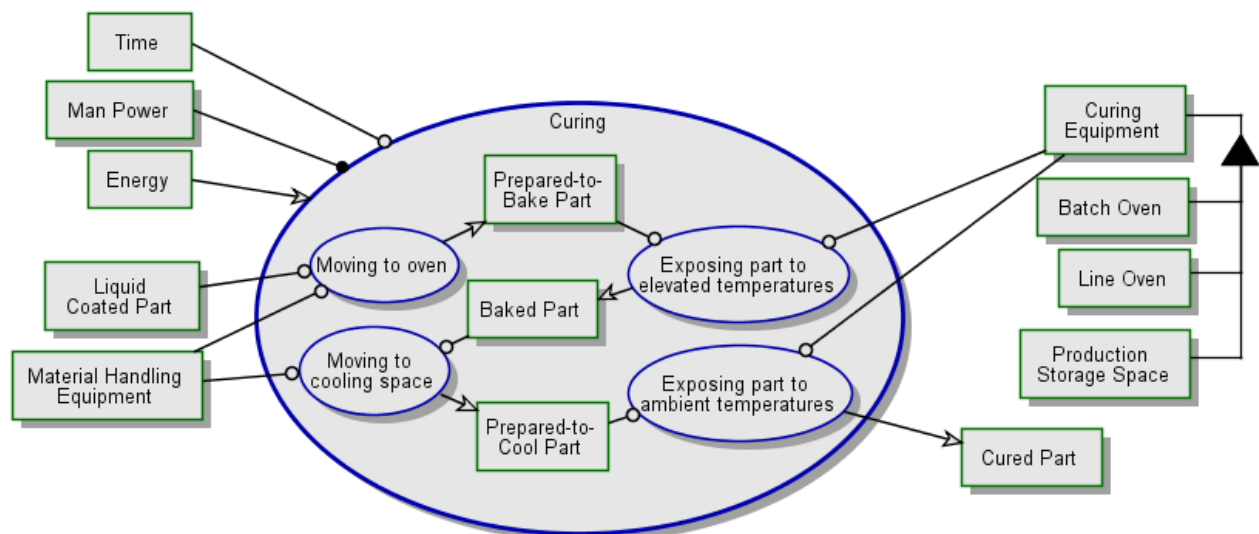


**Figure 41: In-Zoomed Liquid Priming Process Model**

In-zooming into any of the sub-process gives the lowest level of the liquid priming model. The in-zoomed curing process model is displayed in Figure 42. This level allows for a direct link

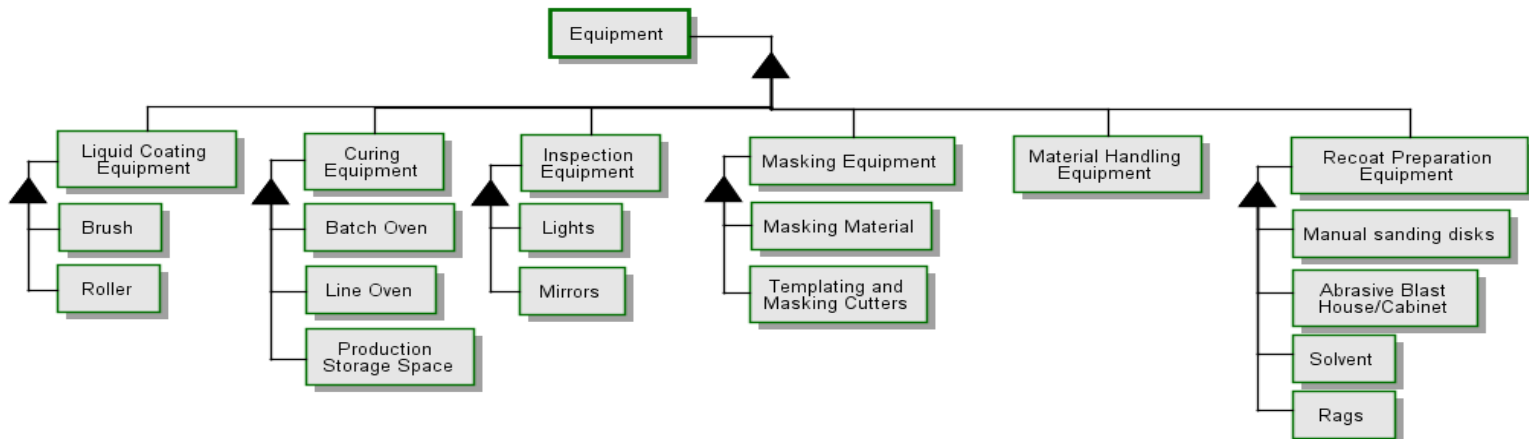


between objects and processes. The moving to oven process requires material handling equipment and a liquid coated part, for example.



**Figure 42: In-Zoomed Curing Model**

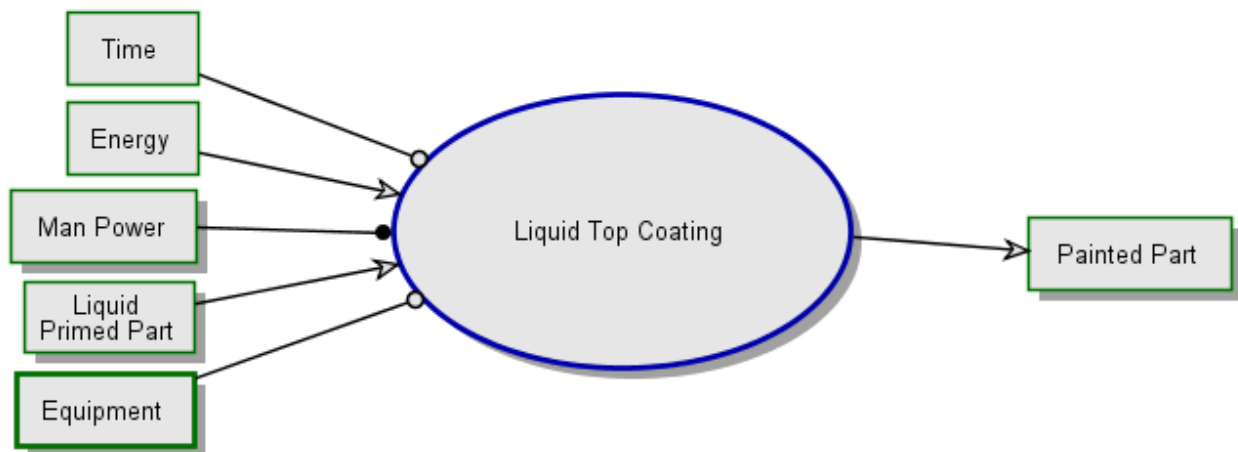
The unfolded equipment set is shown in Figure 39. The set breaks equipment down into more manageable objects that can be used throughout the process model to provide greater detail. In this process model equipment is broken into liquid coating equipment, curing equipment, inspection equipment, masking equipment, material handling equipment and recoat preparation equipment.



**Figure 43: Unfolded Equipment**

#### 4.4.2 Liquid Top Coating

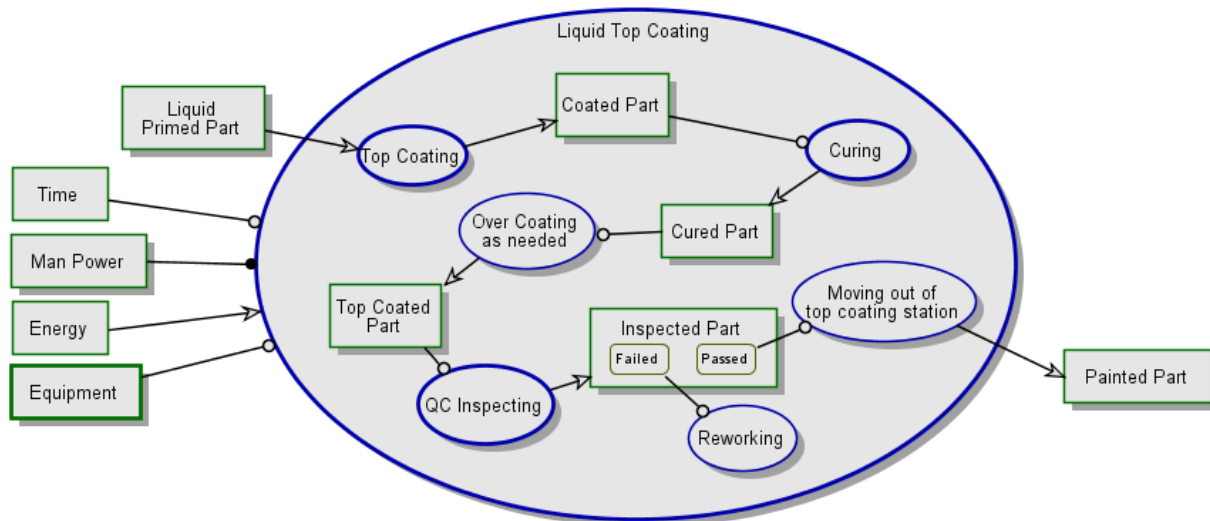
The top level of the liquid top coating process model is displayed in Figure 44. The liquid top coating process requires time and equipment. The process consumes energy and a liquid primed part to yield a painted part.



**Figure 44: Liquid Top Coating Process Model**

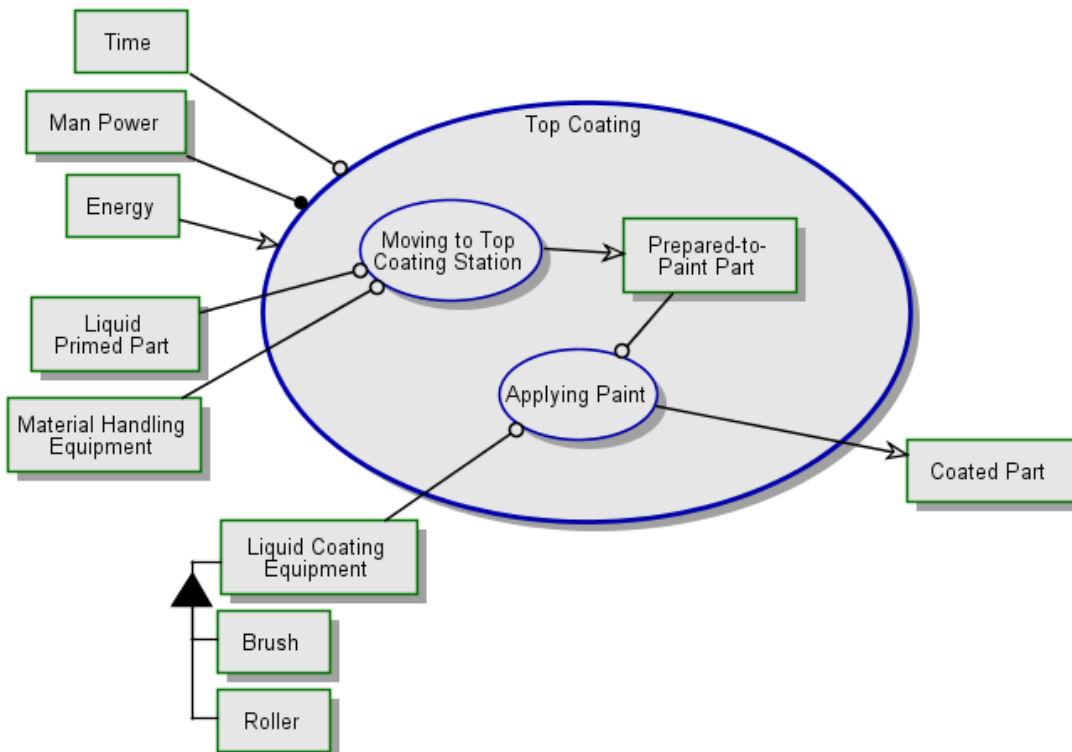
The in-zoomed liquid top coating process model is shown in Figure 45. This process model shows the sub-processes and the specific order needed to complete liquid top coating. To complete the liquid top coating process a part must complete the top coating, curing, and QC inspecting sub-processes.

The QC inspecting sub-process produces the inspected part object with two possible states, failed or passed. A failed inspected part goes to a reworking process while a passed inspected part goes to a move out of top coating station process which leads to the completed painted part.



**Figure 45: In-Zoomed Liquid Top Coat Process Model**

Figure 46 expresses the in-zoomed top coating model. The model allows for processes to be linked to specific equipment. The moving to top coating station sub-process requires material handling equipment and a liquid primed part. Likewise, the applying paint sub-process requires liquid coating equipment and a prepared to paint part.



**Figure 46: In-Zoomed Top Coating Model**

**Figure 47: Unfolded Equipment Set**

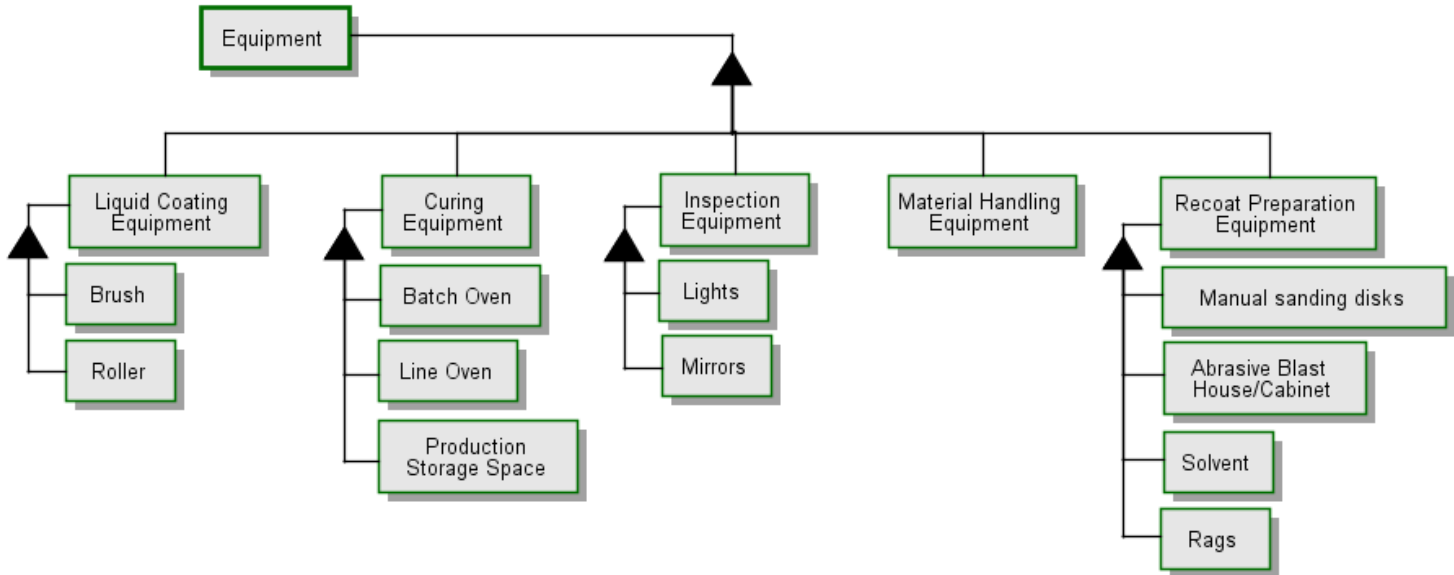
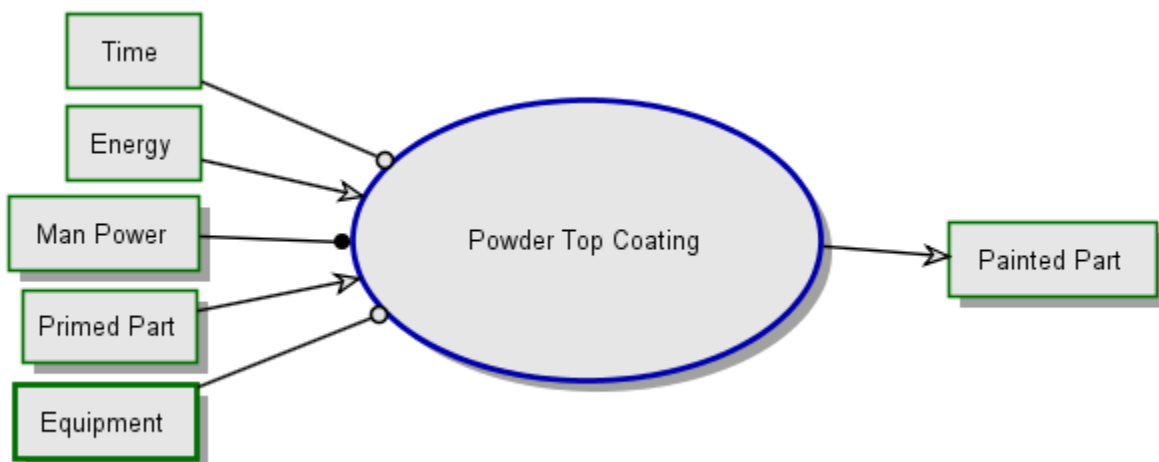


Figure 47 displays the unfolded equipment set. The equipment object is broken into five more functional objects: liquid coating equipment, curing equipment, inspection equipment, material handling equipment and recoat preparation equipment. These objects are then broken down into all objects that apply.

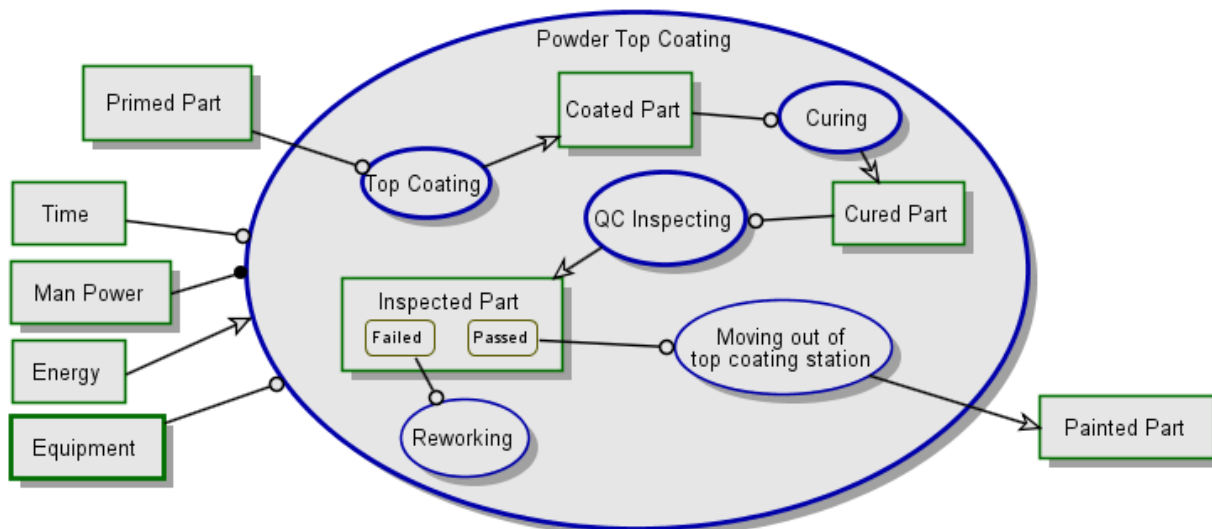
#### 4.4.3 Powder Top Coat

The powder top coating process model is displayed in Figure 48. The process requires time and equipment. Also, the process consumes energy and a primed part to yield a painted part.



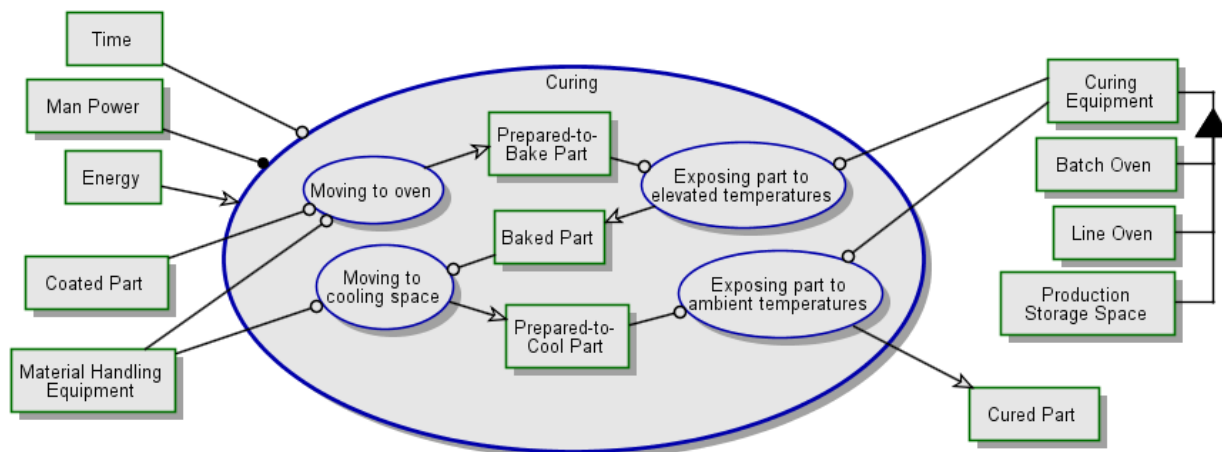
**Figure 48: Powder Top Coat Process Model**

Figure 49 shows the in-zoomed top coating process model. The in-zoomed model illustrates the sub-processes required to complete the powder top coating. Powder top coating requires three processes to be accomplished: top coating, curing and QC inspecting. The inspected part object can be either failed or passed. A failed inspected part goes to a reworking process while a passed inspected part moves out of the top coating station and becomes a completed painted part.



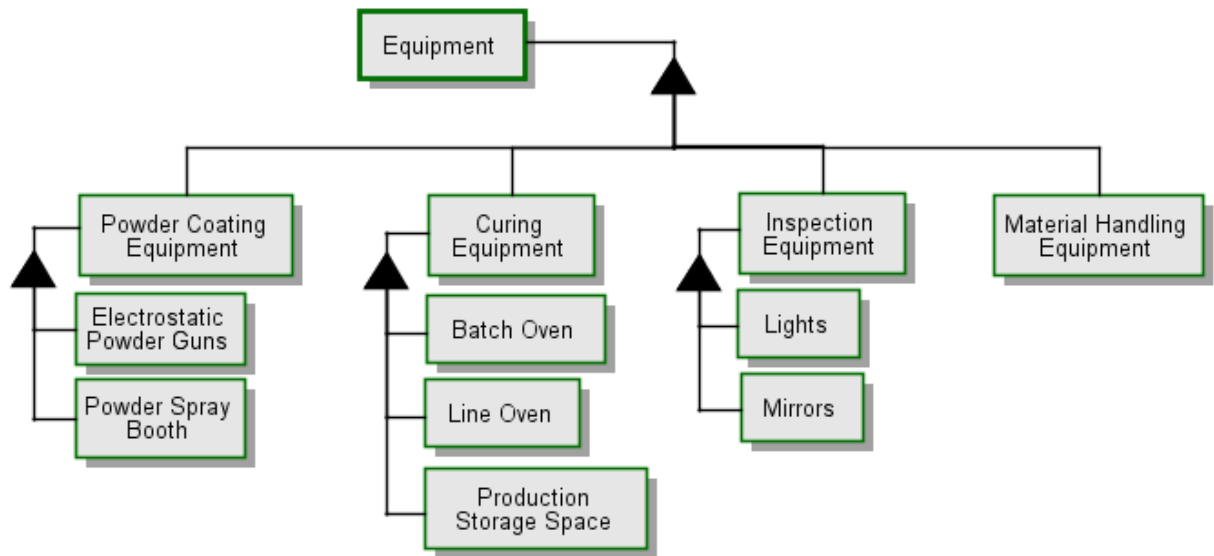
**Figure 49: In-Zoomed Top Coating Process Model**

The in-zoomed curing model is shown in Figure 50. The curing model shows the relation between processes and certain equipment. For example, the two requirements for the moving to oven process are a coated part and material handling equipment. The exposing part to elevated temperatures requires curing equipment and a prepared to bake part. The exposing part to ambient temperatures requires curing equipment and a prepared to cool part. The final output is a 'Cured Part'.



**Figure 50: In-Zoomed Curing Model**

The unfolded equipment set is displayed in Figure 51. Equipment is separated into four objects: powder coating equipment, curing equipment, inspection equipment and material handling equipment. This separation allows for more detail in process models by linking processes to more specific objects.

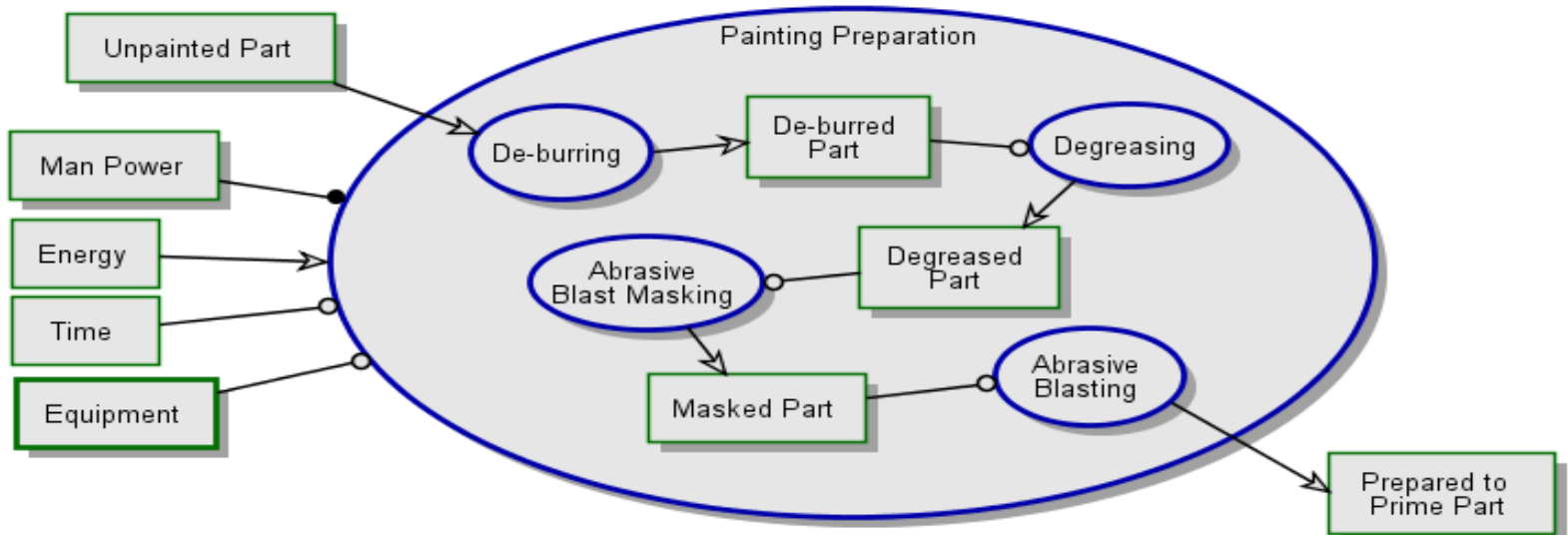


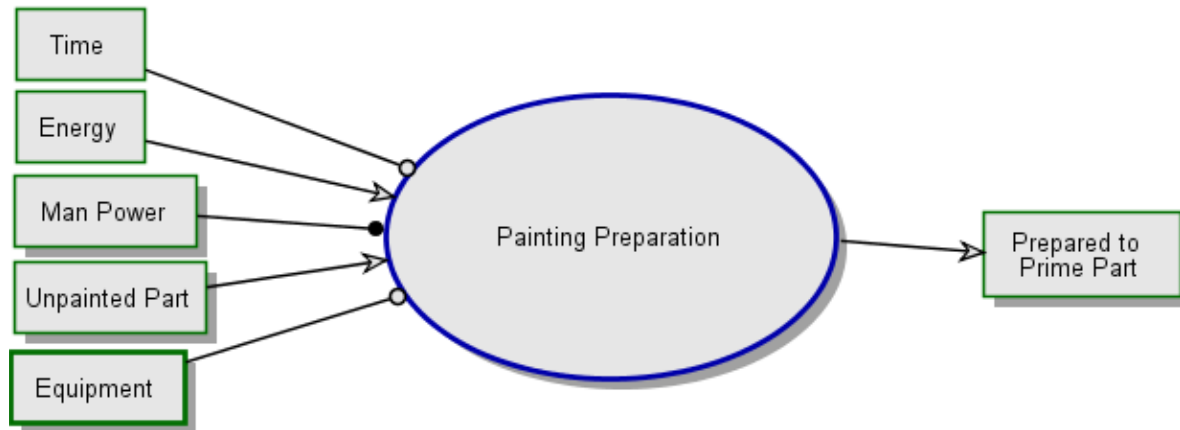
**Figure 51: Unfolded Equipment Set**

#### 4.4.4 Painting Preparation

Figure 52 displays the top level process model for the painting preparation process. The process requires equipment and time to be completed while it consumes energy and an unpainted part. The output of the painting preparation process is a part that is ready to be primed.

**Figure 52: Painting Preparation Model**

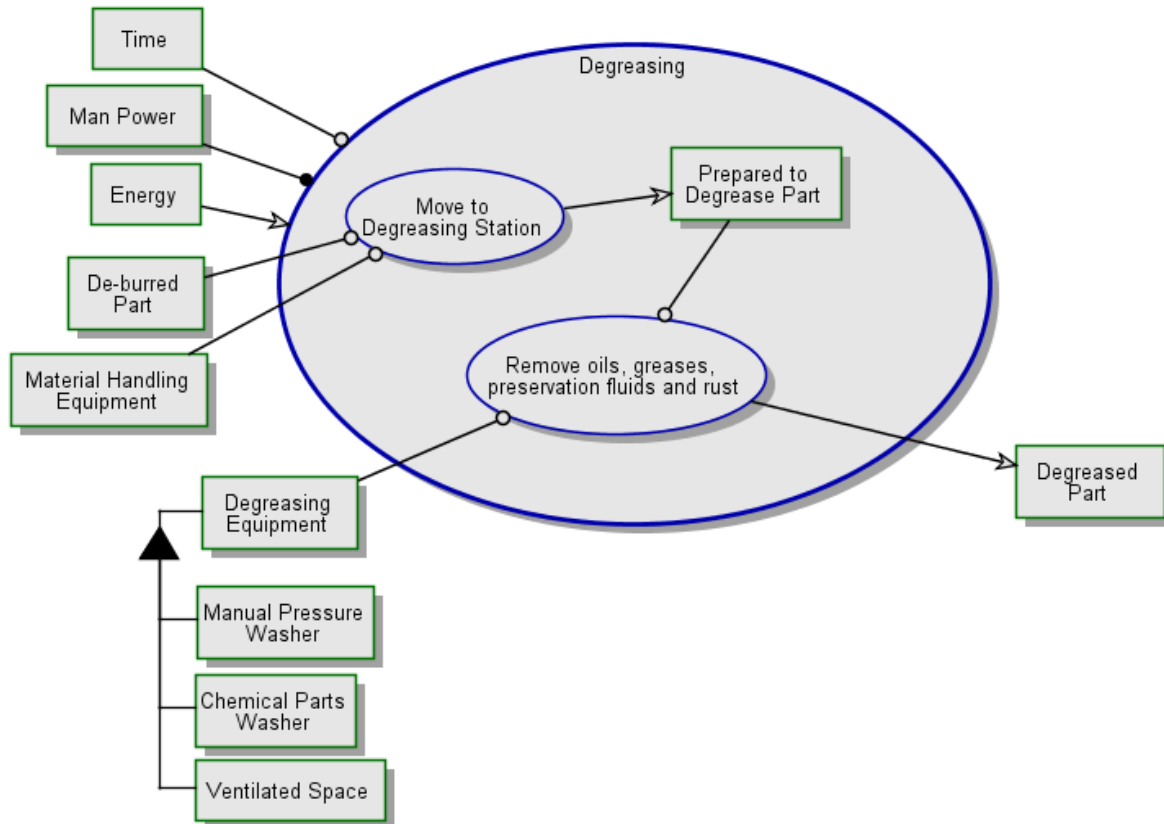




**Figure 53: In-Zoomed Painting Preparation Model**

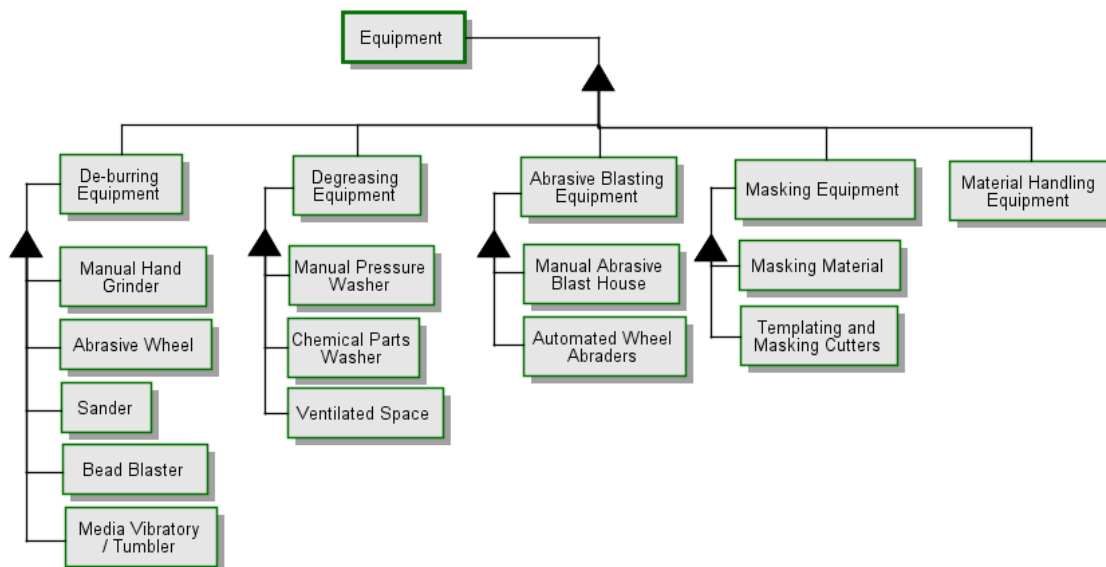
The in-zoomed painting preparation model is shown in Figure 53. This in-zoomed model details the sequential sub-processes involved in the painting preparation process. As shown, the part goes through four sub-processes: de-burring, degreasing, abrasive blast masking and abrasive blasting. Each sub-process yields a specific object, which is required for the next sub-process to begin. All sub-processes have an in-zoomed model to further detail the specifics of that process.

The in-zoomed degreasing process is displayed in Figure 54. In-zooming into the degreasing process allows for further sub-processes to be more detailed. For example, the move to degreasing station sub-process is shown to require a de-burred part and material handling equipment. Likewise the remove oils, grease, preservation fluids and rust sub-process is shown to require degreasing equipment and a prepared to degrease part. Both sub-processes are also at the lowest level possible where further detail cannot be added.



**Figure 54: In-Zoomed Degreasing Model**

Figure 55 displays the unfolded equipment set. This set shows that the equipment object consists of five other objects: de-burring equipment, degreasing equipment, abrasive blasting equipment, masking equipment and material handling equipment.



**Figure 55: Unfolded Equipment Set**

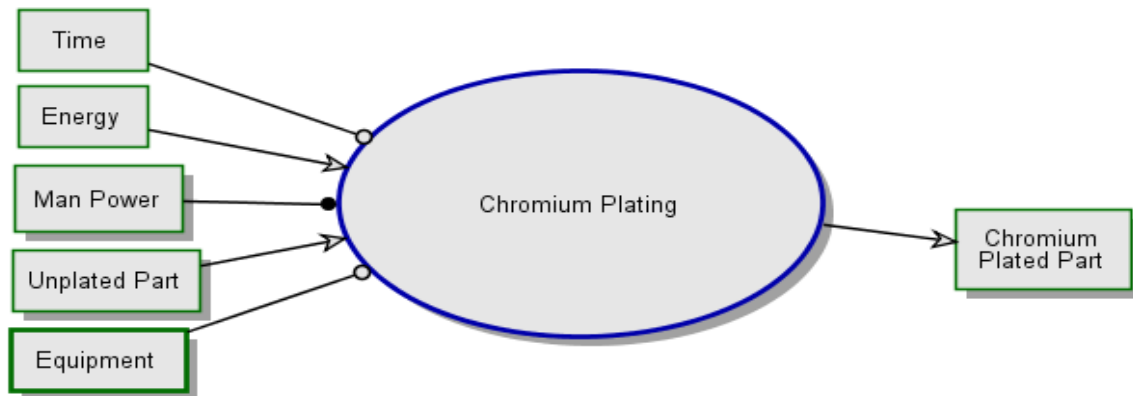


## 4.5 Inorganic Coatings

Inorganic coatings manufacturing processes are more commonly known as plating processes. The following sections describe the developed inorganic coatings manufacturing models.

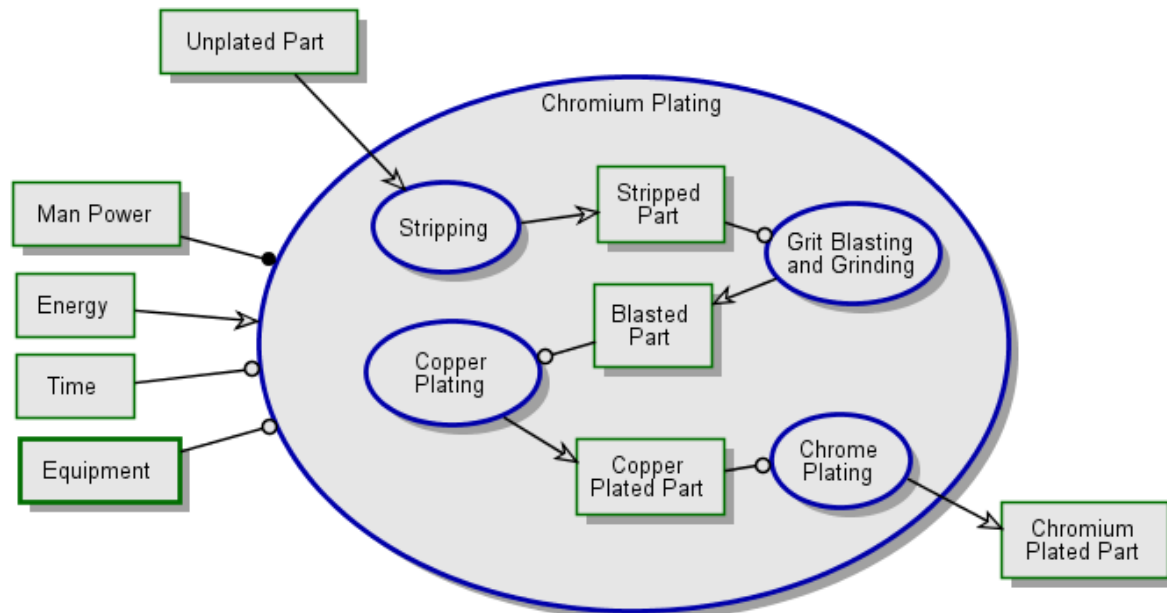
### 4.5.1 Chromium Plating

Figure 56 shows the top level process model for chromium plating. The plating process requires time and equipment while it consumes energy and an unplated part. The output of the chromium plating process is a chromium plated part.



**Figure 56: Chromium Plating Manufacturing Process**

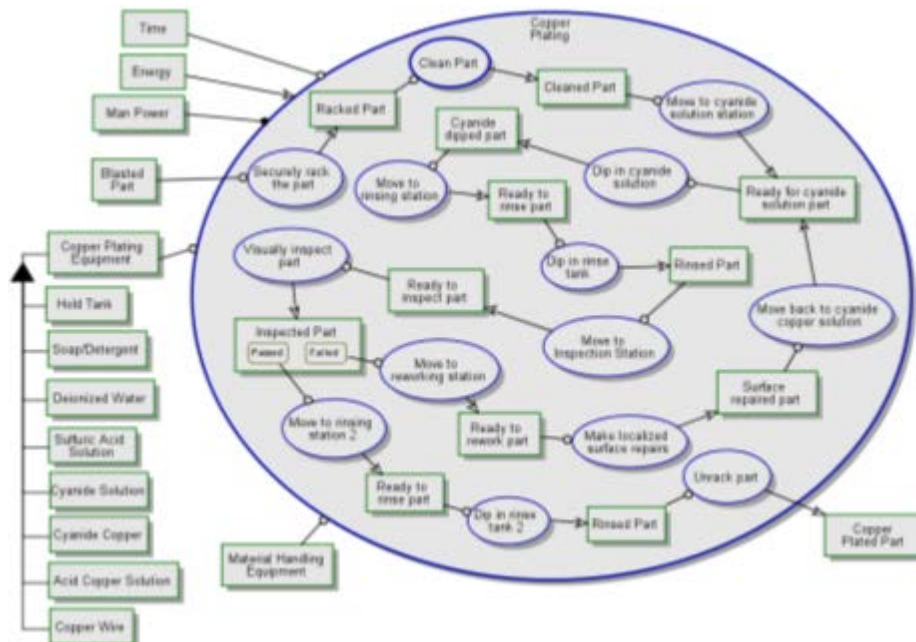
Chromium plating is modeled in greater detail in the in-zoomed process model, shown in Figure 57. The plating process is broken into four sub-processes: stripping, grit blasting and grinding, copper plating and chrome plating. The overall chromium plating process begins when the unplated part begins the stripping process. Each sub-process has its own in-zoomed model to further detail the processes.



**Figure 57: In-Zoomed Chromium Plating Manufacturing Process**

The in-zoomed copper plating process is shown in Figure 58. This model shows in-depth detail of the process, such as copper plating requires copper plating equipment and material handling equipment.

The inspected part object can be one of two states, passed or failed. The state of this object determines how the part will proceed to complete the process. If the part passed the visual inspection it will continue towards the end of the process. However, if the part failed the visual inspection it will be required to rework through previous steps.



**Figure 58: In-Zoomed Copper Plating Process**

The unfolded equipment set is shown in Figure 59. This set shows the breakdown of the equipment involved in the chromium plating process. Equipment is broken into five categories: stripping equipment, grit blasting and grinding equipment, copper plating equipment, plating equipment and material handling equipment. Each type of equipment can be broken down into all of its parts as shown.



Figure 59

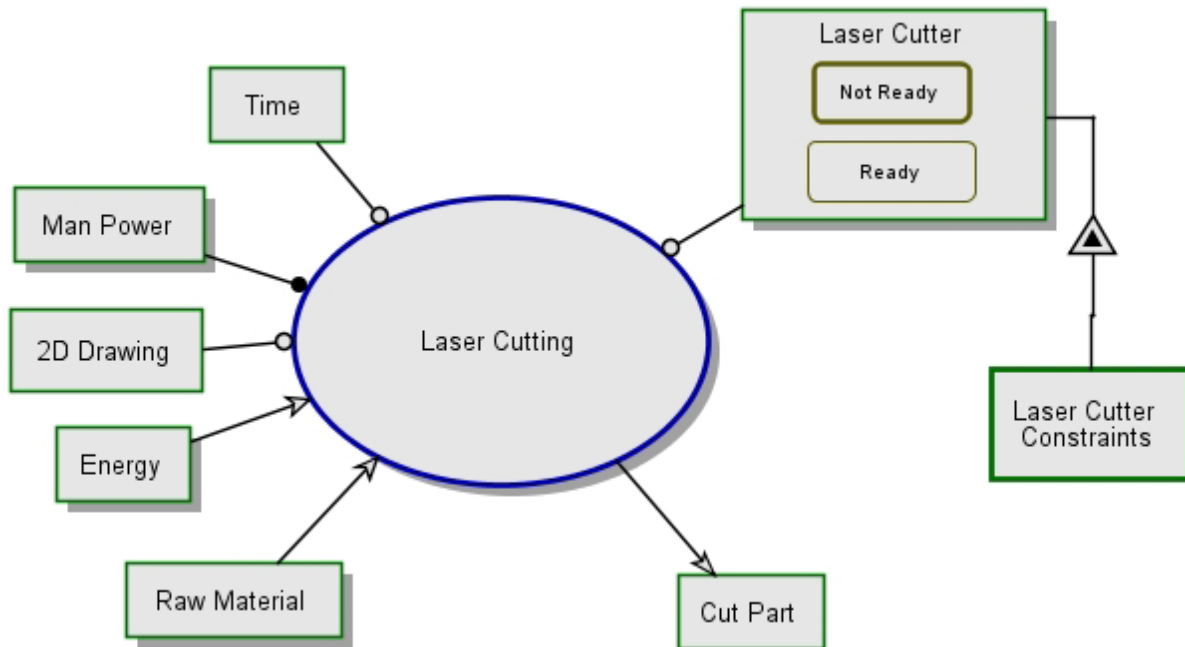
## 4.6 Sheet and Plate Metal Cutting

Four manufacturing processes were modeled for sheet and plate cutting. These include laser cutting, oxyfuel cutting, plasma cutting, and waterjet cutting.

### 4.6.1 Laser Cutting

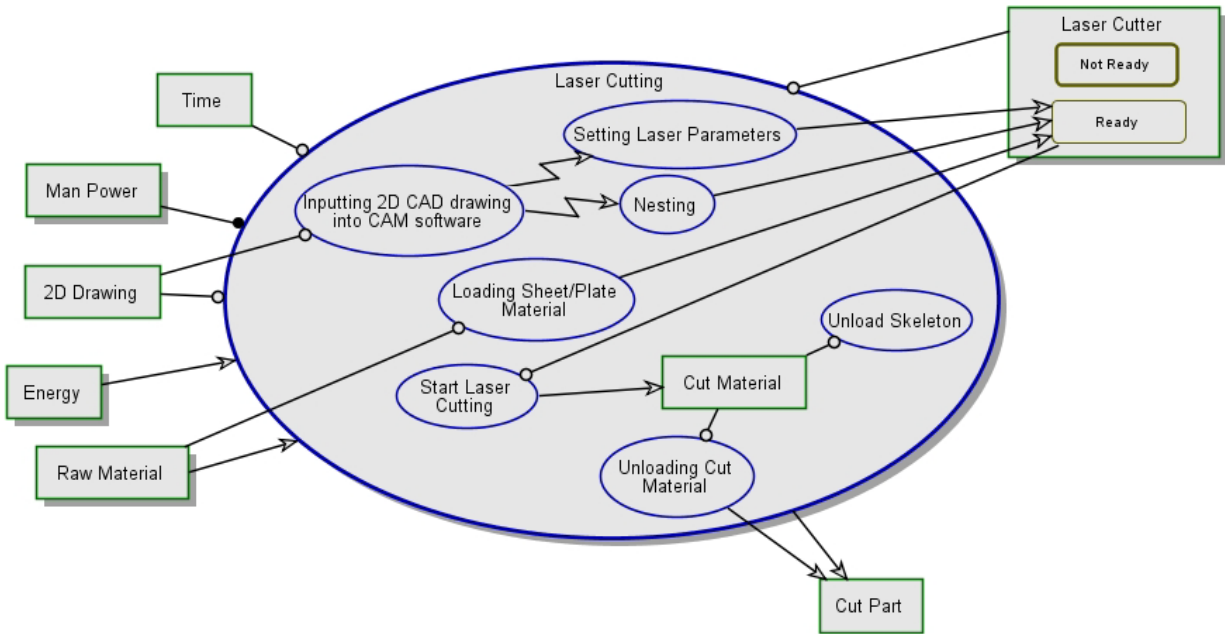
Figure 60 displays the top level process model for the laser cutting process. The process requires two major inputs, raw material (in the form of plates or sheets) and energy required to execute the process). In addition, there are three non-intelligent enablers for the process: 1) time, 2) a 2D drawing, and 3) the laser cutting machine. The laser cutter can be represented in a state of *Ready* or *Not Ready* based on a resource constraint set (discuss further below) and the information contained in the 2D drawing.

The output of the laser cutting process is the cut part from the raw material plate.



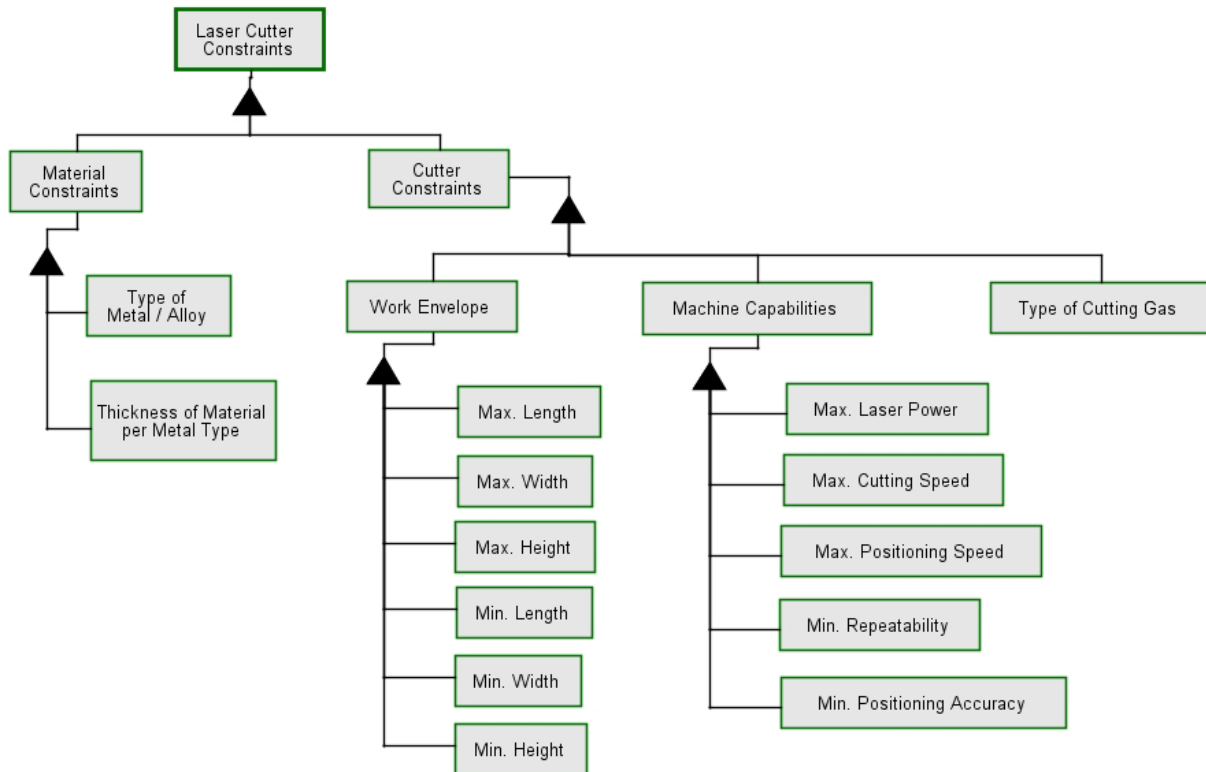
**Figure 60: Laser Cutting Manufacturing Process**

Greater detail of the laser cutting process can be obtained by “in-zooming” on the Laser Cutting process in the Opcat modeling software. The in-zoomed laser process model is shown in Figure 61, where there exist several sub-processes. The overall laser cutting process is initiated by a sub-process that loads a 2D CAD drawing of the part to be cut. From here a machine set-up sub-process and nesting process are defined. The set-up and nesting sub-processes, along with the sub-process for loading the raw material onto the cutting machine are all required to be completed for the laser cutting machine (resource) to be changed to a state of *Ready*.



**Figure 61: In-Zoomed Laser Cutting Manufacturing Process**

Figure 62 displays the constraint set for the laser cutter object. The instantiation of the constraints occurs when linking a laser cutting machine resource model to the laser cutting process model. For instance, one laser cutter may have a maximum material thickness that is smaller than what is required by the part to be cut. Therefore, the laser cutting process cannot reach a state of *Ready*, and the process is not capable of making that part. The laser cutter constraints are divided into two major categories: 1) Material constraints, and 2) Cutter constraints.

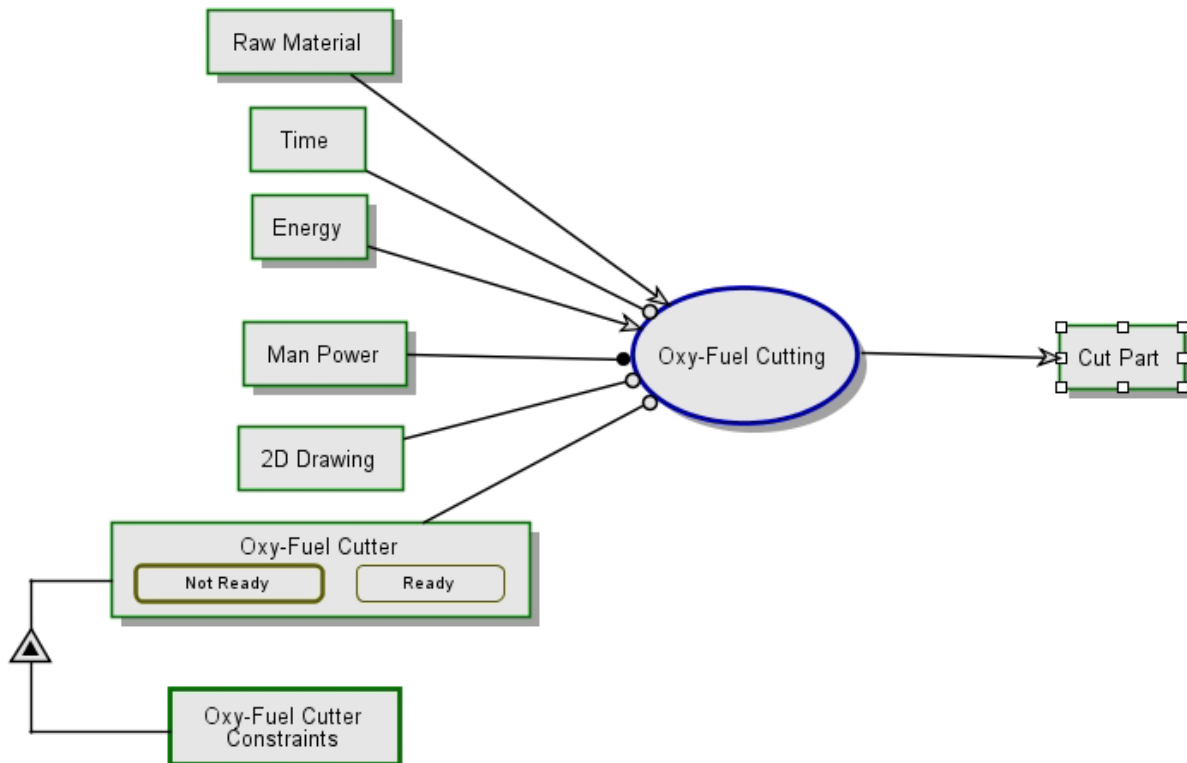


**Figure 62: Laser Cutter Constraint Set**

#### 4.6.2 Oxy-Fuel Cutting

Figure 63 displays the top level process model for the oxy-fuel cutting process. The process requires two major inputs, raw material (in the form of plates or sheets) and energy required to execute the process). In addition, there are three non-intelligent enablers for the process: 1) time, 2) a 2D drawing, and 3) the oxy-fuel cutting machine. The oxy-fuel cutter can be represented in a state of *Ready* or *Not Ready* based on a resource constraint set (discuss further below) and the information contained in the 2D drawing.

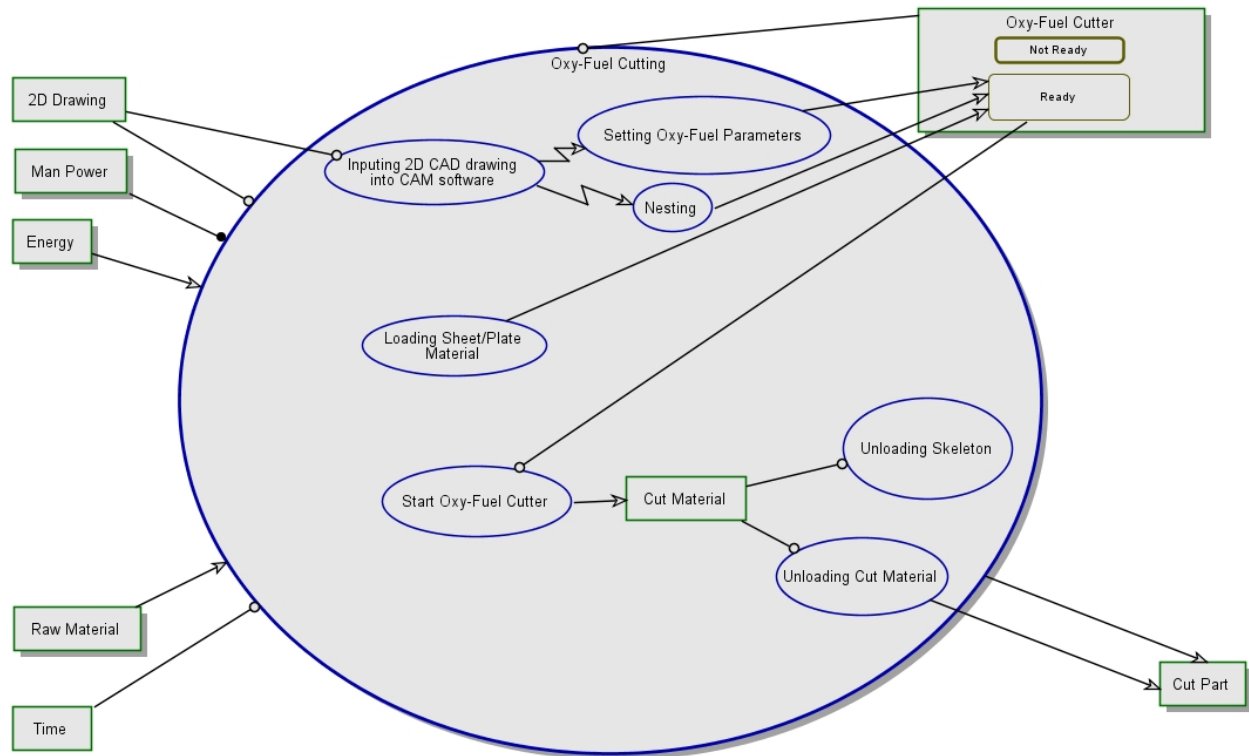
The output of the oxy-fuel cutting process is the cut part from the raw material plate.



**Figure 63: Oxy-fuel Cutting Manufacturing Process**

Greater detail of the oxy-fuel cutting process can be obtained by “in-zooming” on the Oxy-Fuel Cutting process in the Opcat modeling software. The in-zoomed oxy-fuel process model is shown in Figure 64, where there exist several sub-processes. The overall oxy-fuel cutting process is initiated by a sub-process that loads a 2D CAD drawing of the part to be cut. From here a machine set-up sub-process and nesting process are defined. The set-up and nesting sub-processes, along with the sub-process for loading the raw material onto the cutting machine are all required to be completed for the oxy-fuel cutting machine (resource) to be changed to a state of *Ready*.

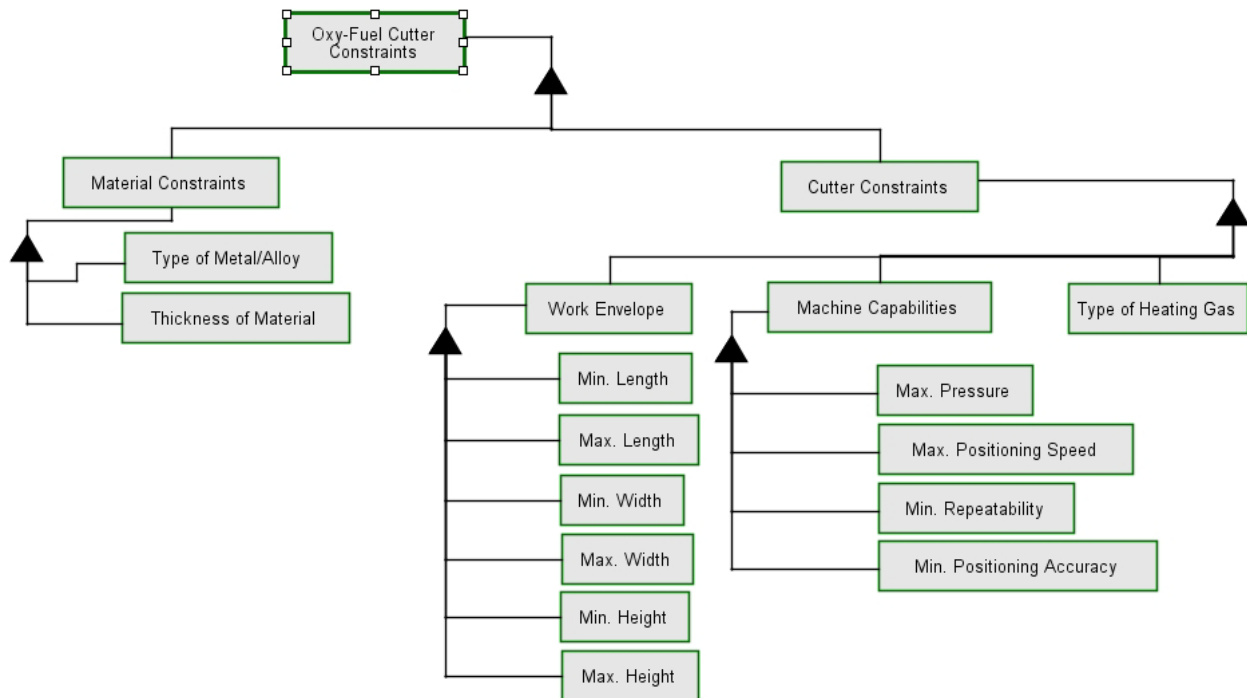
Once the *Ready* state has been achieved, a sub-process exists for the start-up of the oxy-fuel cutting machine and actual cutting of the sheet/plate. The result of this sub-process is the cut plate, which acts as an input to the final two sub-processes: Unloading the Skeleton (waste) and Unloading the Cut Part(s).



**Figure 64: In-Zoomed Oxy-fuel Cutting Manufacturing Process**

Figure 65 displays the constraint set for the oxy-fuel cutter object. The instantiation of the constraints occurs when linking an oxy-fuel cutting machine resource model to the oxy-fuel cutting process model. For instance, one oxy-fuel cutter may have a work envelop that is smaller than what is required by the part to be cut. Therefore, the oxy-fuel cutting process cannot reach a state of *Ready*, and the process is not capable of making that part. The oxy-fuel cutter constraints are divided into two major categories: 1) Material constraints, and 2) Cutter constraints.



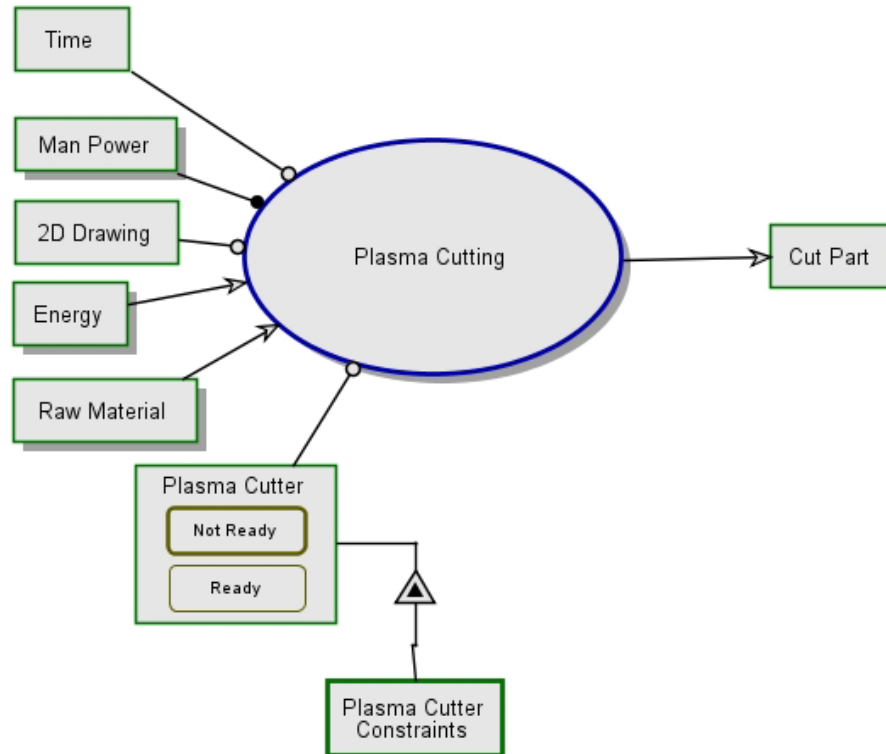


**Figure 65: Oxy-fuel Cutter Constraint Set**

### 4.6.3 Plasma Cutting

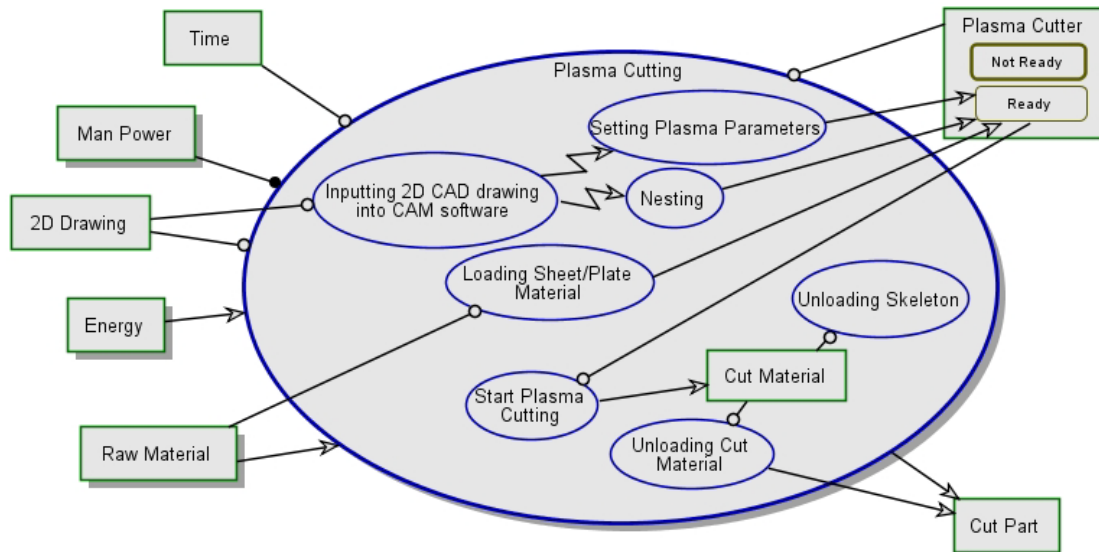
Figure 66 displays the top level process model for the plasma cutting process. The process requires two major inputs, raw material (in the form of plates or sheets) and energy required to execute the process). In addition, there are three non-intelligent enablers for the process: 1) time, 2) a 2D drawing, and 3) the plasma cutting machine. The plasma cutter can be represented in a state of *Ready* or *Not Ready* based on a resource constraint set (discuss further below) and the information contained in the 2D drawing.

The output of the plasma cutting process is the cut part from the raw material plate.



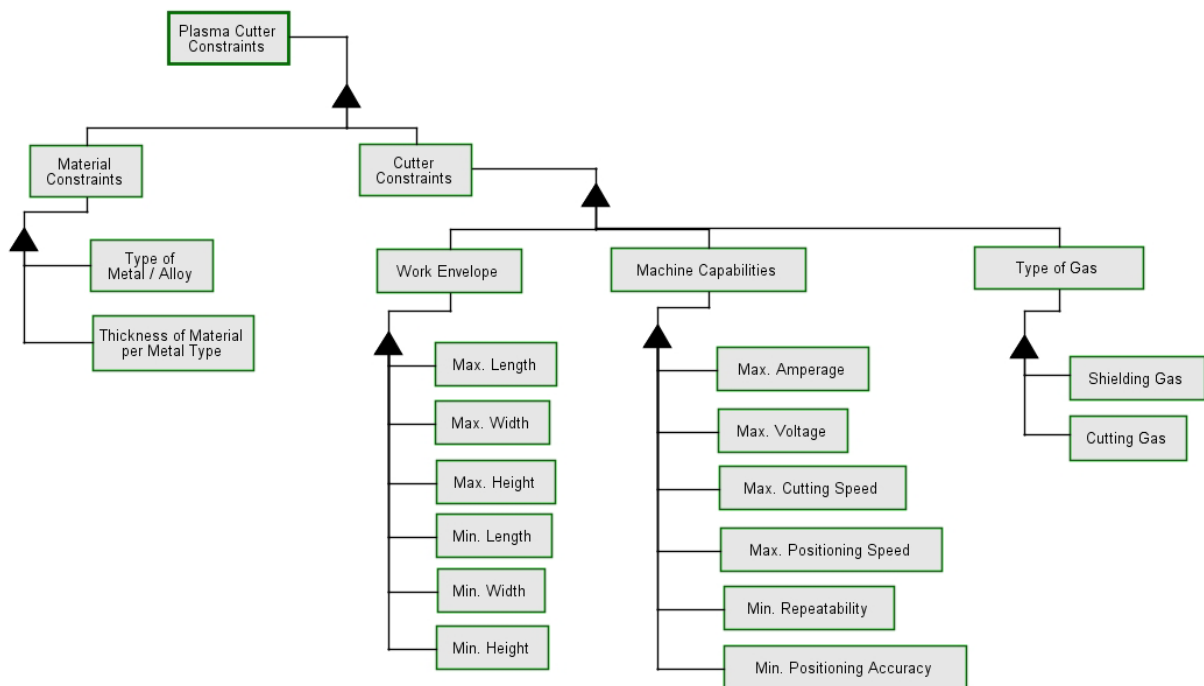
**Figure 66: Plasma Cutting Manufacturing Process**

Greater detail of the laser cutting process can be obtained by “in-zooming” on the Plasma Cutting process in the Opcat modeling software. The in-zoomed plasma process model is shown in Figure 67, where there exist several sub-processes. The overall plasma cutting process is initiated by a sub-process that loads a 2D CAD drawing of the part to be cut. From here a machine set-up sub-process and nesting process are defined. The set-up and nesting sub-processes, along with the sub-process for loading the raw material onto the cutting machine are all required to be completed for the plasma cutting machine (resource) to be changed to a state of *Ready*.



**Figure 67: In-Zoomed Plasma Cutting Manufacturing Process**

Figure 68 displays the constraint set for the plasma cutter object. The instantiation of the constraints occurs when linking a plasma cutting machine resource model to the plasma cutting process model. For instance, one plasma cutter may have a work envelop that is smaller than what is required by the part to be cut. Therefore, the plasma cutting process cannot reach a state of *Ready*, and the process is not capable of making that part. The plasma cutter constraints are divided into two major categories: 1) Material constraints, and 2) Cutter constraints.



**Figure 68: Plasma Cutter Constraint Set**

#### 4.6.4 Water Jet Cutting

Figure 69 displays the top level process model for the water jet cutting process. The process requires two major inputs, raw material (in the form of plates or sheets) and energy required to execute the process). In addition, there are three non-intelligent enablers for the process: 1) time, 2) a 2D drawing, and 3) the water jet cutting machine. The water jet cutter can be represented in a state of *Ready* or *Not Ready* based on a resource constraint set (discuss further below) and the information contained in the 2D drawing.

The output of the water jet cutting process is the cut part from the raw material plate.

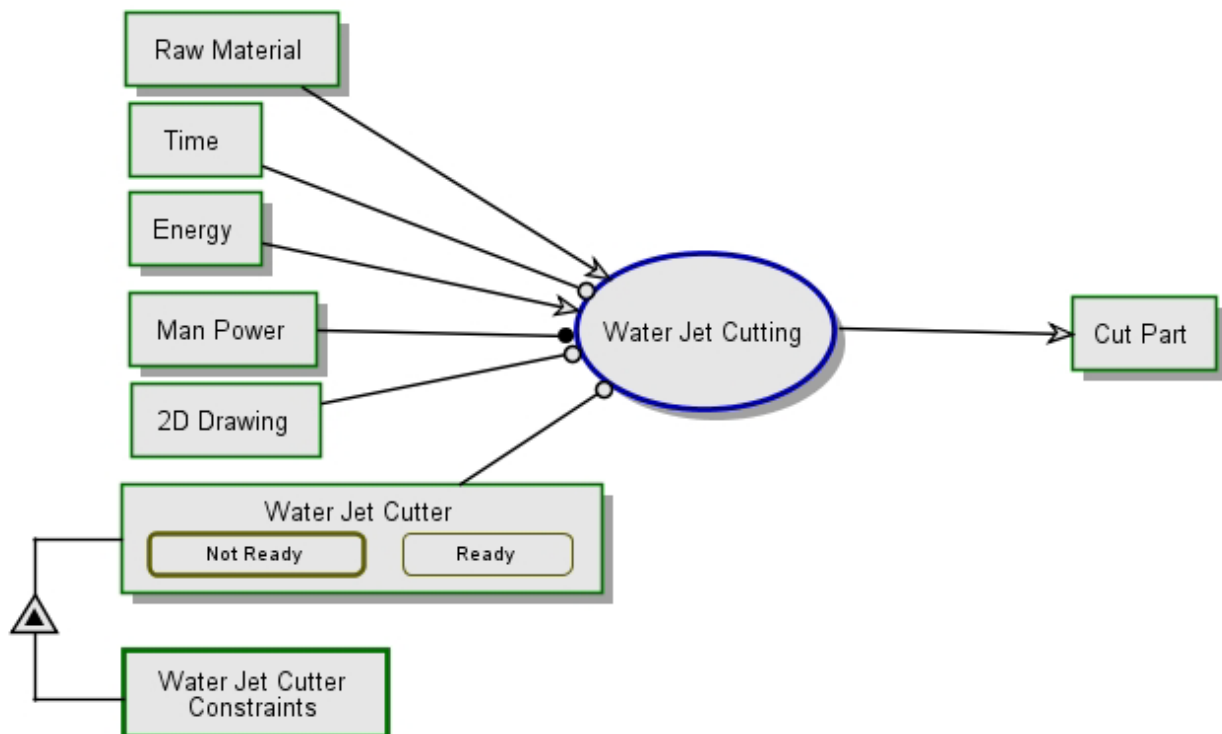
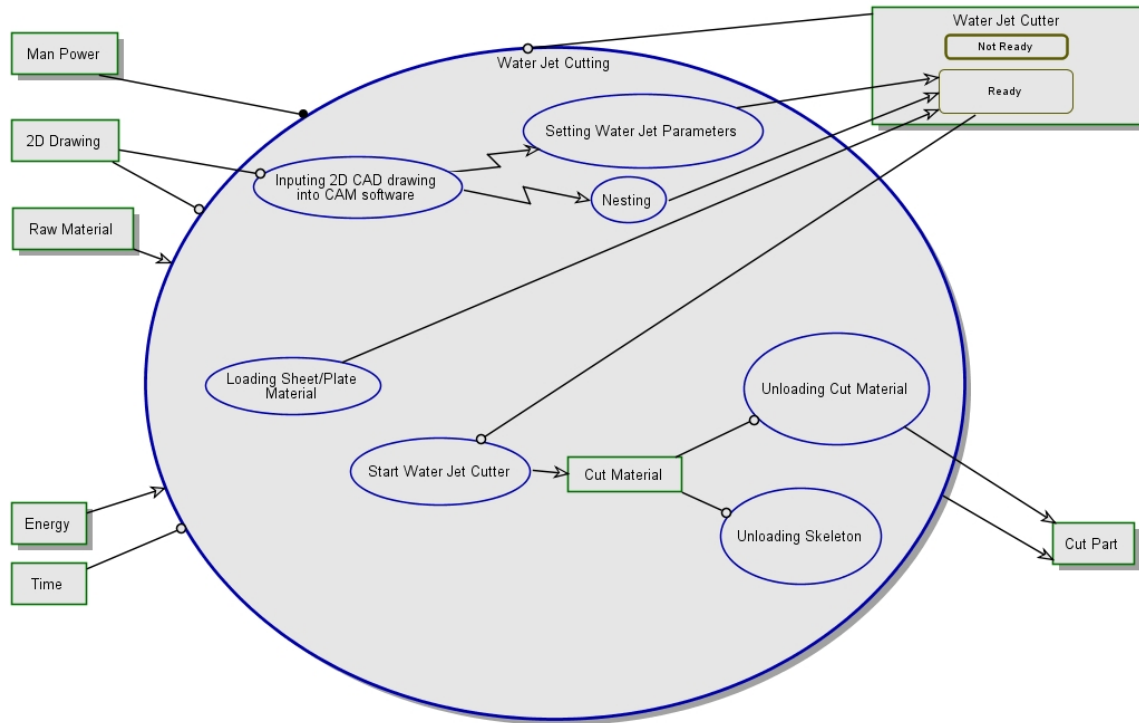


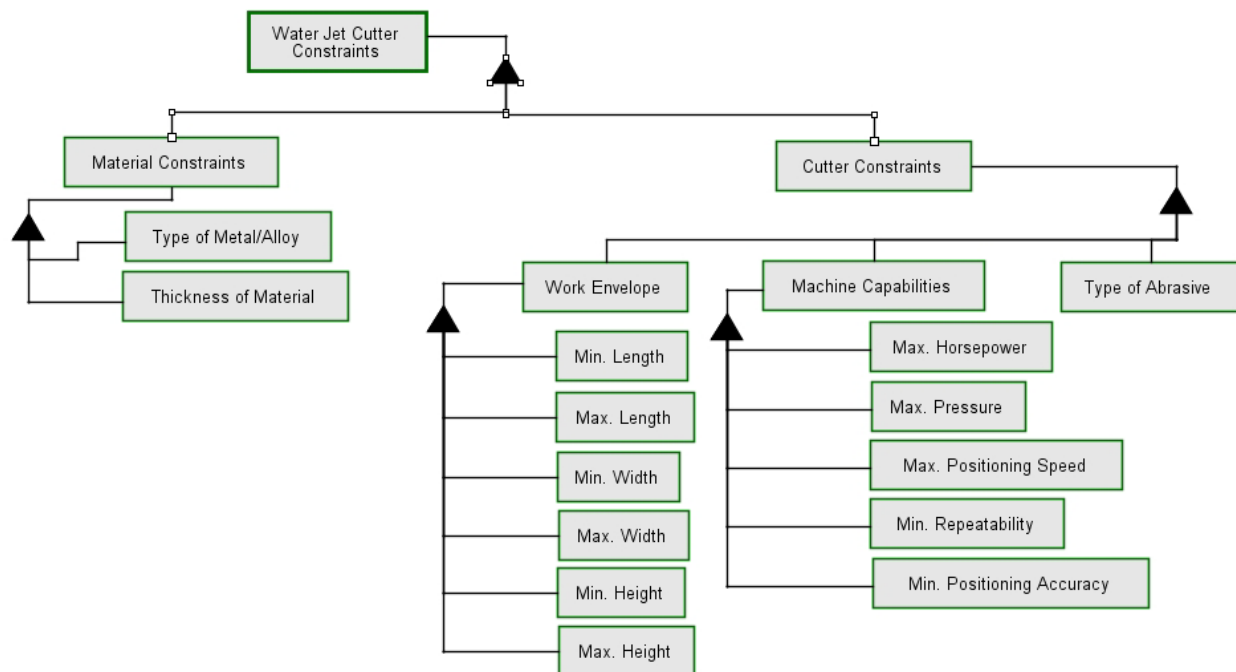
Figure 69: Water Jet Cutting Manufacturing Process

Greater detail of the water jet cutting process can be obtained by “in-zooming” on the Water Jet Cutting process in the Opcat modeling software. The in-zoomed water jet process model is shown in Figure 70, where there exist several sub-processes. The overall water jet cutting process is initiated by a sub-process that loads a 2D CAD drawing of the part to be cut. From here a machine set-up sub-process and nesting process are defined. The set-up and nesting sub-processes, along with the sub-process for loading the raw material onto the cutting machine are all required to be completed for the water jet cutting machine (resource) to be changed to a state of *Ready*.



**Figure 70: In-Zoomed Water Jet Cutting Manufacturing Process**

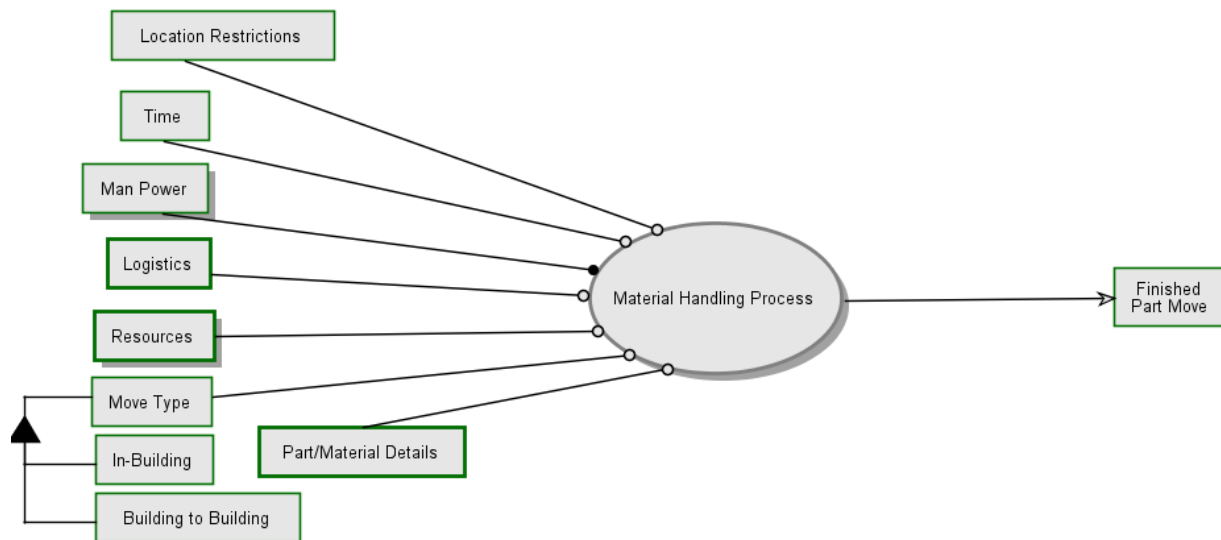
Figure 71 displays the constraint set for the water jet cutter object. The instantiation of the constraints occurs when linking a water jet cutting machine resource model to the water jet cutting process model. For instance, one water jet cutter may have a maximum material thickness that is smaller than what is required by the part to be cut. Therefore, the water jet cutting process cannot reach a state of *Ready*, and the process is not capable of making that part. The water jet cutter constraints are divided into two major categories: 1) Material constraints, and 2) Cutter constraints.



**Figure 71: Water Jet Cutter Constraint Set**

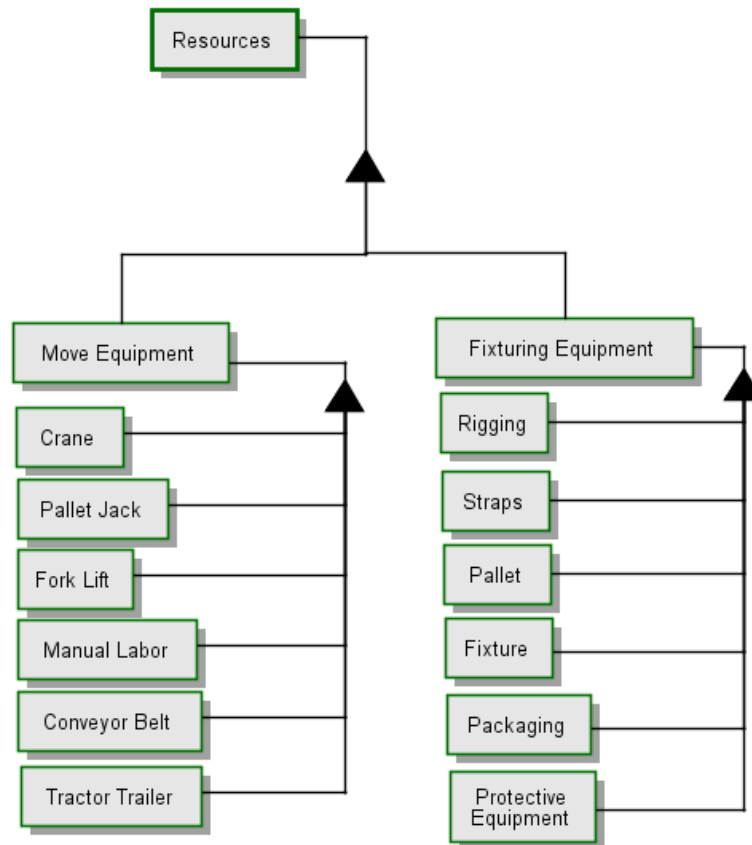
#### 4.7 Material Handling

Figure 72 displays the top level process model for many types of material handling. The process contains six non-intelligent enablers; part/material details, logistics, resources, time, location restrictions and move type. The output of the material handling process is a finished part move.



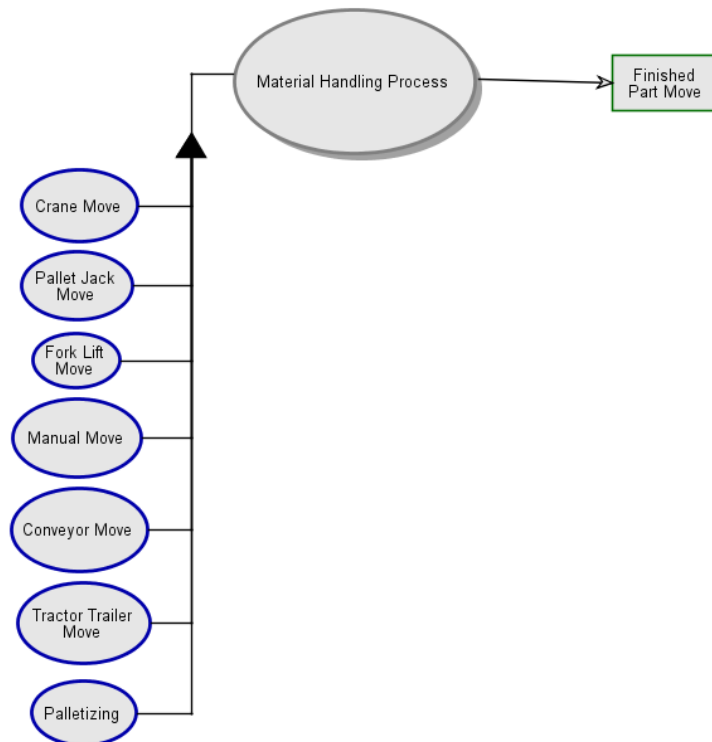
**Figure 72: Material Handling Manufacturing Process Model**

The resources and logistics non-intelligent enablers can be unfolded to show individual components. The resources unfold contains move equipment and fixturing equipment. Each is further broken down to their individual components which can be seen in Figure 73.



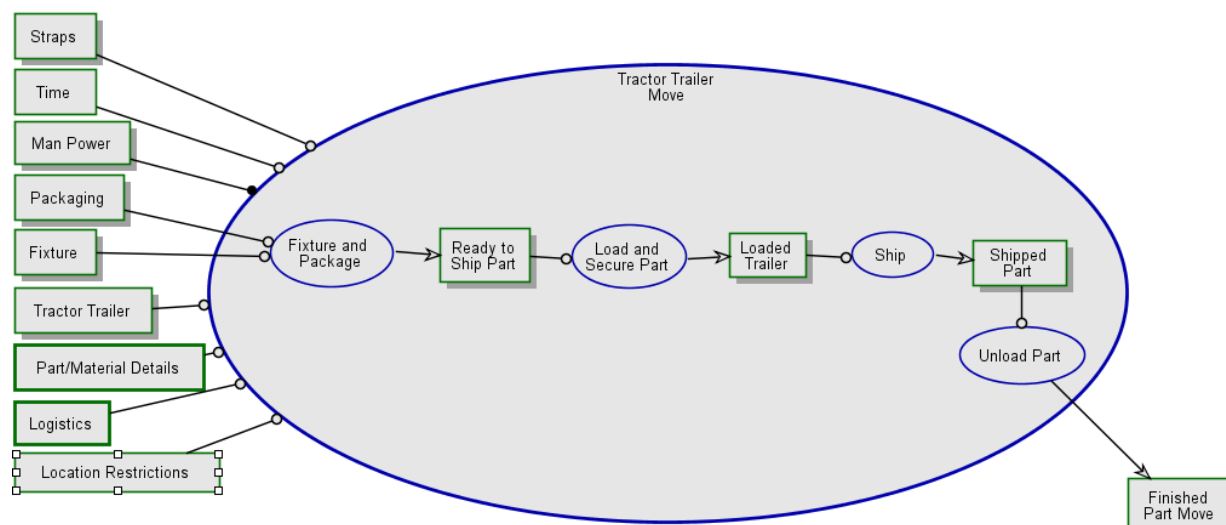
**Figure 73: Material Handling Manufacturing Process Resources Unfold**

The material handling process can be unfolded to reveal the various sub-processes available for material handling. These processes are tractor trailer move, crane move, pallet jack move, fork lift move, manual move, conveyor move, and palletizing. This unfold is depicted in Figure 74.



**Figure 74: Material Handling Manufacturing Process Unfold**

Each sub process is in-zoomed to provide greater detail. Each in-zoom contains specific move equipment and fixturing equipment found in the resources unfold. An example of an in-zoomed sub process can be found in Figure 75. This sub process pertains to the tractor trailer move and pulls tractor trailer from the move equipment and fixturing and packaging from fixturing equipment.



**Figure 75: In-Zoomed Tractor Trailer Move**

#### **4.8 Dimensional Inspection and Control**

Dimensional Inspection and Control is a critical support process in the manufacturing of IFVs, and the original MMLs lacked sufficient representation of inspection equipment that is required



to perform these processes. Most manufacturing facilities capable of NC machining, plate/sheet processing, casting, welding, and mechanical assembly are well equipped with standard measurement hand tools (e.g., calipers; micrometers, digital and manual, depth gauges, etc.), and it is well-known when these resources are needed in part and small assembly manufacturing.

We instead, focused on enhancing our MML resources with non-standard equipment that is required for larger and more controlled alignment and inspection requirements, including IFV power pack alignment, suspension attachment measurement and alignment, and critical weld inspection (i.e., full-penetration structural joints).

For large dimensional control, alignments, and inspection, the following resource categories were represented in the MML:

- CMM gages
- Measuring Arms
- Laser Trackers

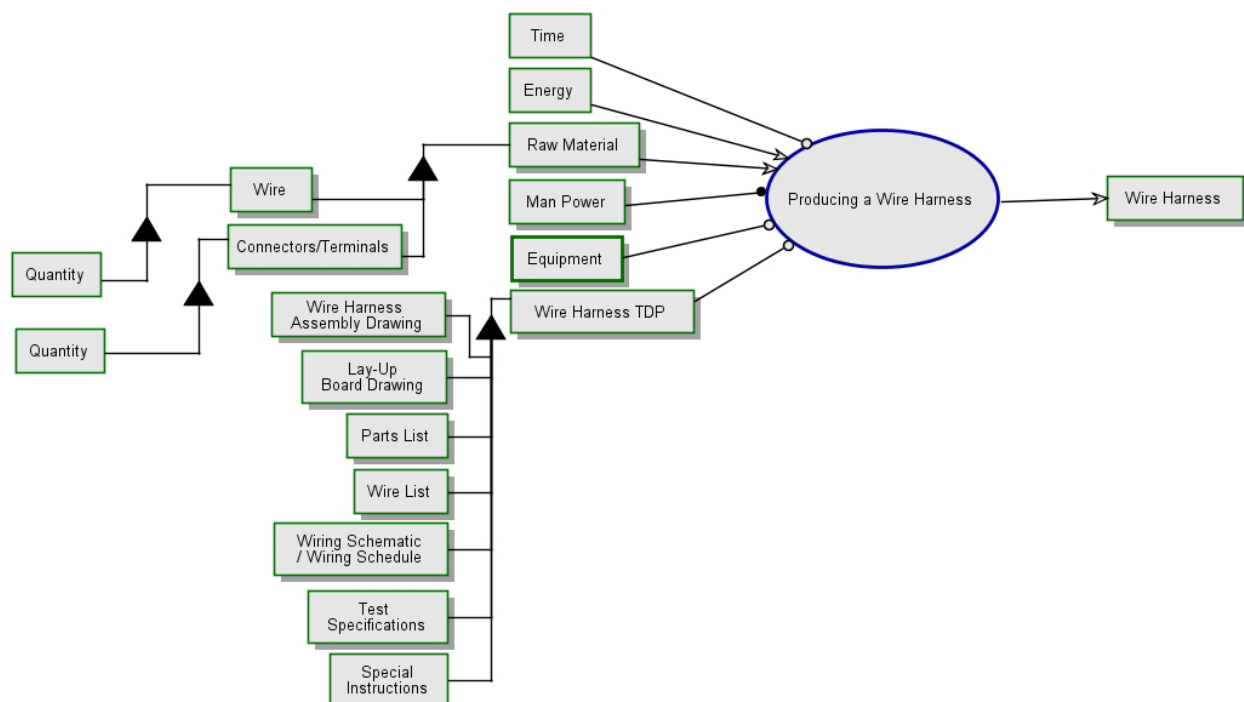
For critical weld inspection, the following resource categories were represented in the MML:

- X-Ray Inspection
- Ultrasonic Inspection
- Dye Penetrant Inspection
- Magnetic Particle Inspection (MT)
- Liquid Penetrant Inspection (MT)

#### **4.9 Wire Harness Assembly**

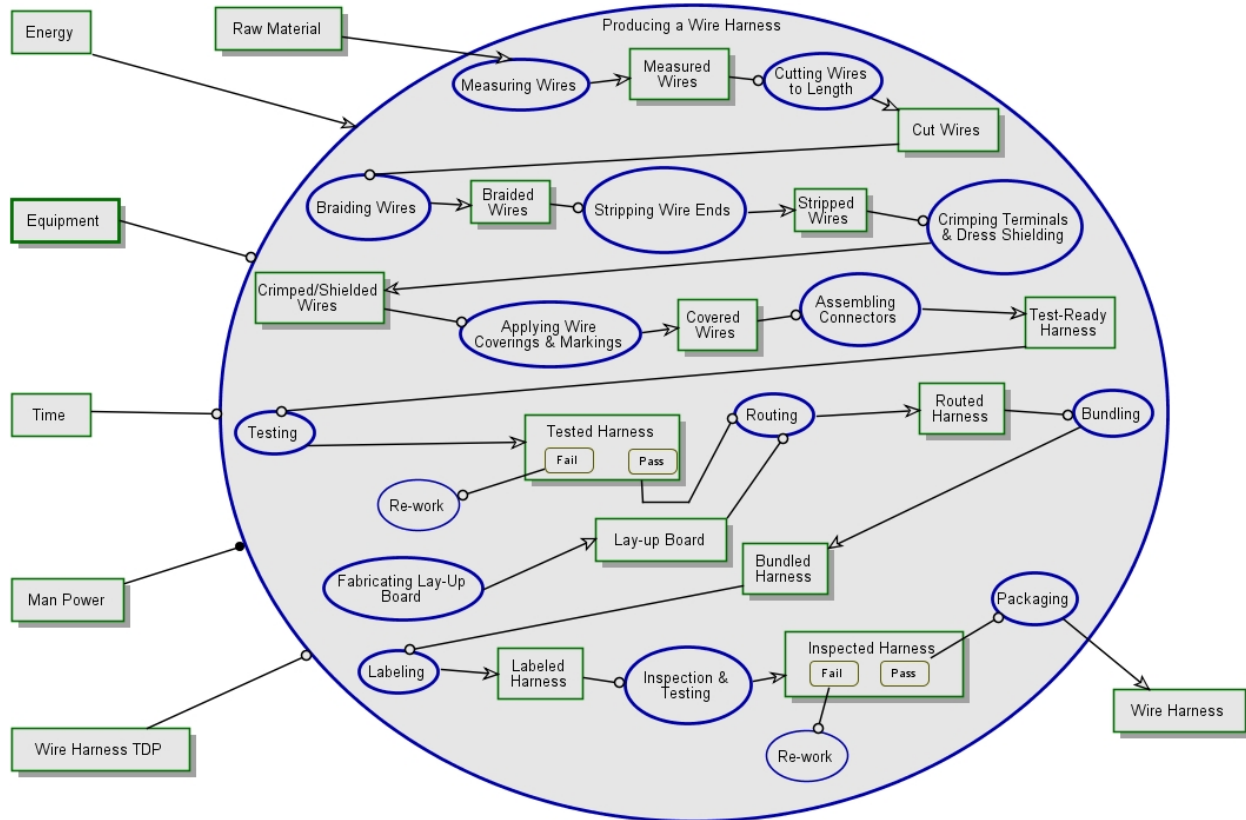
Figure 76 displays the top-level process model for producing a wire harness. The process requires two major inputs the form of various raw materials and energy in order to complete the process. In addition, there are three non-intelligent enablers for the process, time, equipment, and the wire harness TDP. The wire harness technical data package consists of seven items, wire harness assembly drawing, lay-up board drawing, parts list, wire list, wire schematic/wiring schedule, test specifications, and special instructions. The process also requires an intelligent enabler in the form of man power.

The output of the producing a wire harness process is a wire harness.



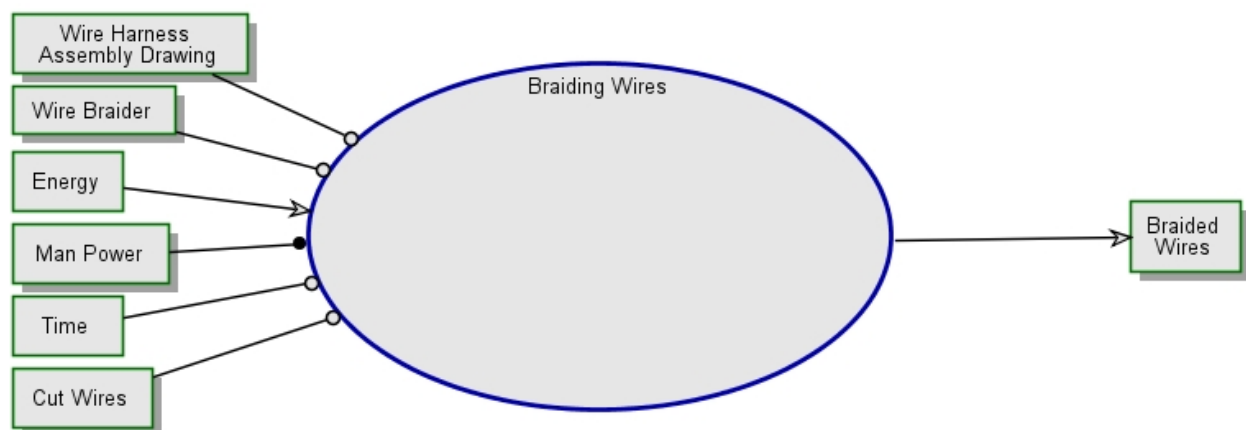
**Figure 76: Wire Harness Manufacturing Process**

Greater detail of the wire harness production process can be obtained by “in-zooming” on the Producing a Wire Harness process in the OpCat modeling software. The in-zoomed wire harness production model is shown in Figure 77, where it outlines the several sub-processes necessary to produce a wire harness as well as each sub-processes output. Each sub-process is completed in the order shown in Figure 77 with the exception of fabricating the lay-up board. This sub-process can be completed at any time before the routing process takes place.



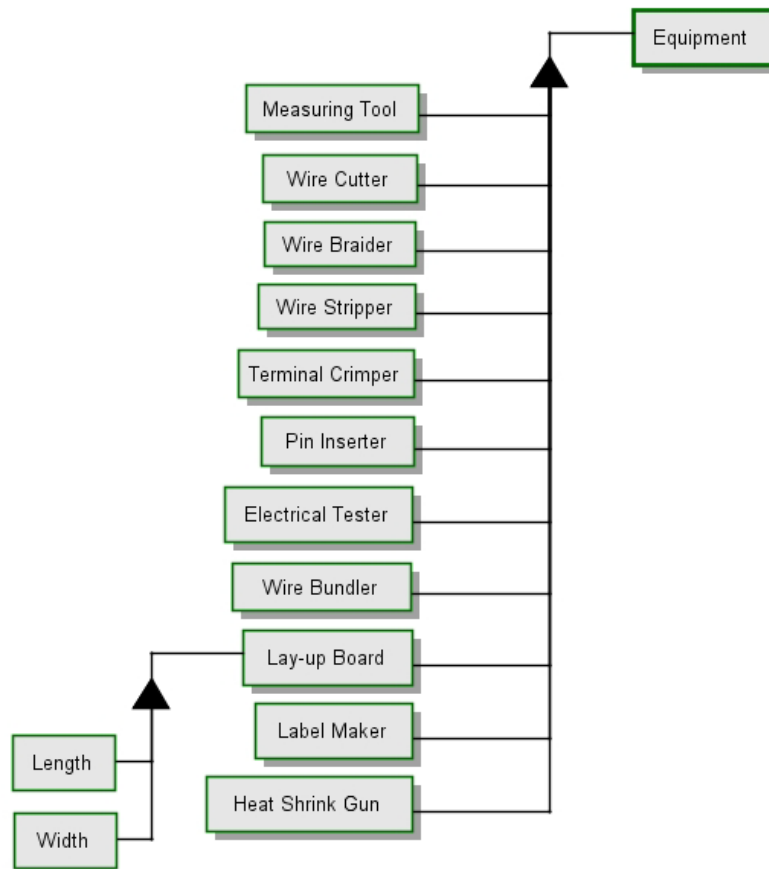
**Figure 77: In-Zoomed Wire Harness Manufacturing Process**

Each sub-process can be further in-zoomed to outline the specific equipment necessary as well as the specific item(s) needed to complete the task from the wire harness technical data package. The in-zooms also include the specific output of that sub-process. An example of sub-process in-zooms can be seen in Figure 78.



**Figure 78: In-Zoomed Sub-Process of Braiding Wires**

Figure 79 displays all the equipment necessary to produce a wire harness. One or more of these tools is used in each sub-process and is linked in the appropriate sub-process.



**Figure 79: Wire Harness Manufacturing Equipment**

## **4.10 Machining**

For machining-based processing methods, two activities were covered in the C2M2L project. First, enhancements were made to the manufacturing model library (MML) with regard to primary machining activities, as well as associated resource and central material/quality models. Second, a parametric process planning case study was conducted to identify important characteristics of the interaction of the MML with future-planned process planning activities.

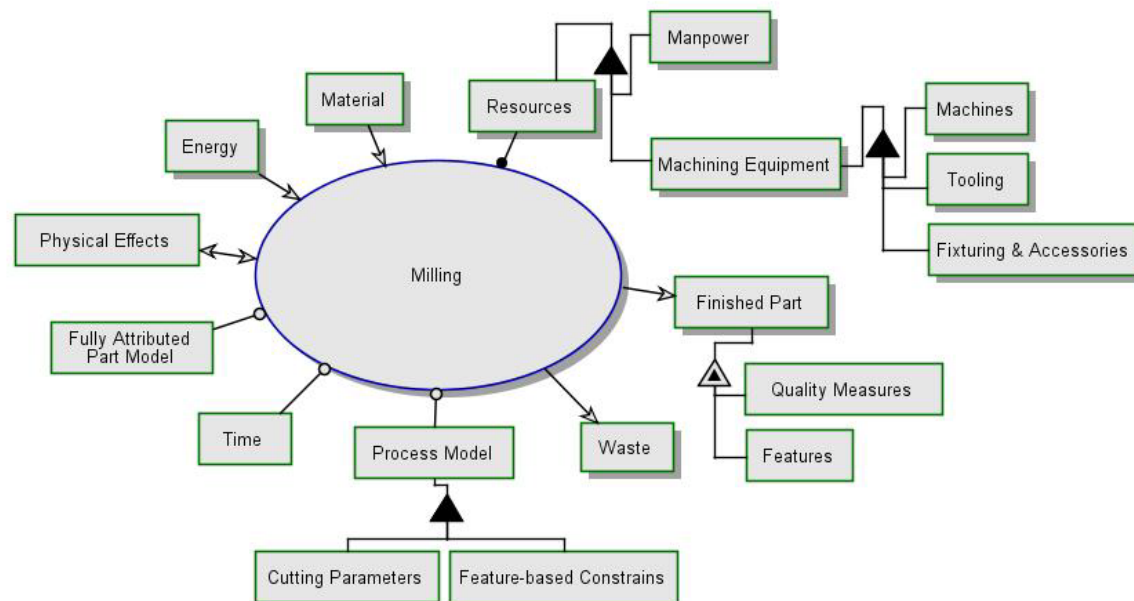
### **4.10.1 Manufacturing model library**

The manufacturing model library (MML) was populated with process and resource models for key machining-based activities, including drilling, turning and grinding. OPCAT modeling software was used to model the hierarchical nature of these process descriptions, as is pictured below. The generic machining process model details process-specific parameters, feature-based constraints for those processes and compatibility with specific resources (e.g., machines, tooling). The generic process description describes a common set of quality parameters, material inputs and workpiece characteristics for each of these processes. Process-specific models for grinding, milling and turning were developed and compared/contrasted with the existing MML's description for these processes. The differences were cataloged to include updated descriptions for machining-based processes.

#### **4.10.1.1 High-level process description**

An example of the high-level process description used to describe each of these processes is shown in Figure 80. The inputs into the milling process include work materials, energy

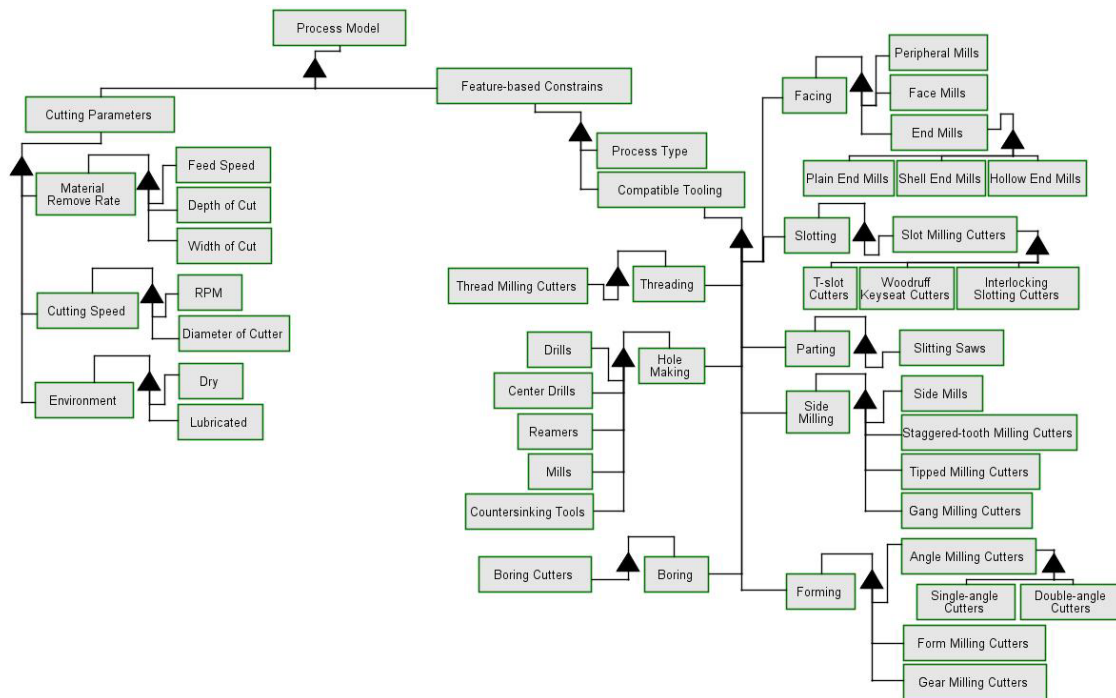
consumption, a fully attributed part model, resources and a process model. Outputs of the process include a finished manufactured part and waste.



**Figure 80: Milling High-Level Process Model**

#### 4.10.1.2 Process model

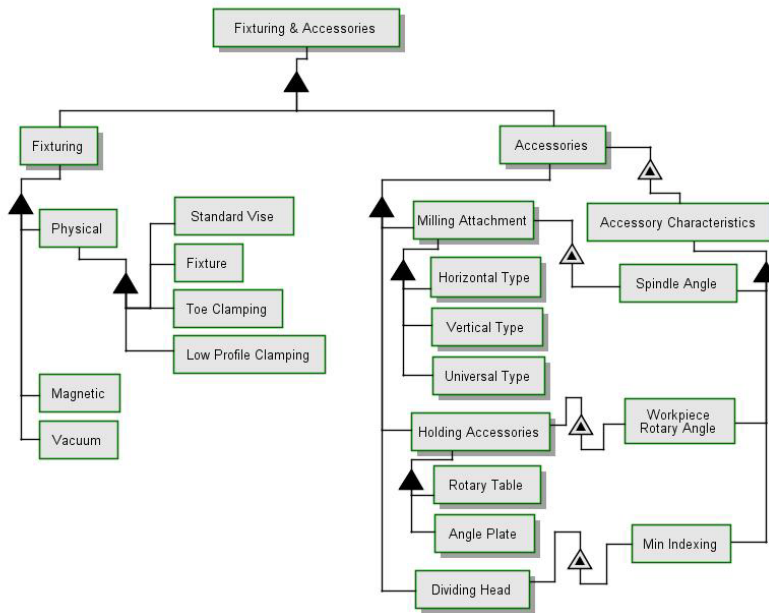
Each machining-based process also has an associated process model as shown in Figure 81. For milling, the process model includes cutting parameters necessarily specified for the process plan and feature-related constraints for the milling process. The feature-based constraints are tied directly to a given list of compatible tooling types within the general operation of milling, as well as the sub-processes involved. It was found that several key sub-processes within individual process groups were missing from the original MML (GA Tech and MCPML). For example, the original MML did not include side, slot and thread milling. The addition of this more comprehensive list of subtypes will facilitate a straightforward query to the machining data handbook for suggested machining conditions. A critical step beyond the C2M2L project will be to link feature taxonomy to the individual processes and their subtypes. This important element will need to be addressed when the automatic process-planning element of the IFAB project is better developed.



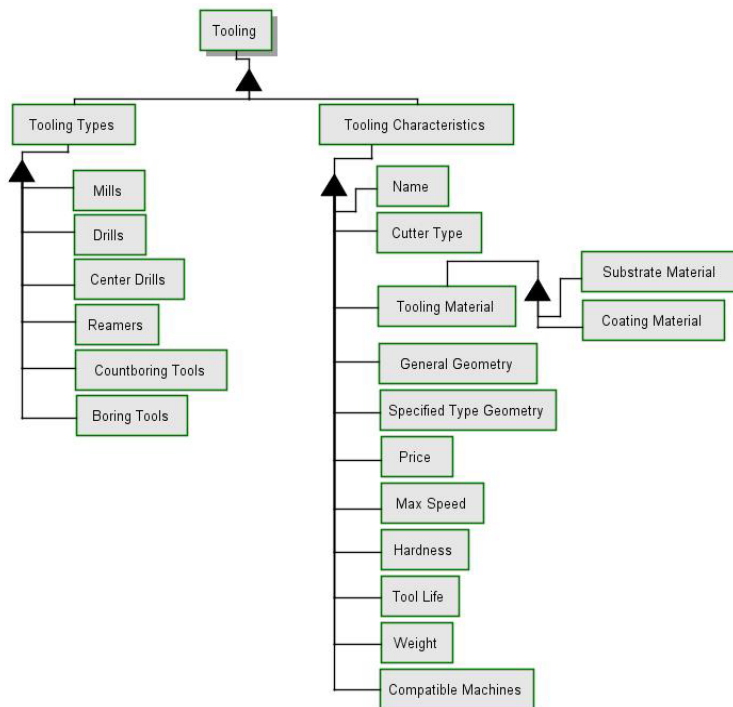
**Figure 81: Milling Process Model**

#### 4.10.1.3 Resource model

Each machining-based process has associated resource models for machines, fixturing and tooling. The below figure shows examples of the fixturing (Figure 82) and tooling (Figure 83) associated with milling-type processes. It was found that the original MML included a variety of fixtures that well covered the gamut of possible fixture types. However, elements including clamping area were not included and are part of the updated MML. Clamping area may be important for process-level requirements specified by the manufacturing performers in the IFAB foundry. With regard to tooling, the original MML was lacking in several key areas. For example, the original MML only included two types of tooling materials in describing tooling resources: uncoated carbide and high speed steel. Further, the original MML only included the most basic geometry parameters (diameter, overall length, number of flutes) for each main type of cutter. To remedy these elements, the updated MML includes a more expansive list of possible tooling materials, including various coatings for carbide tooling, which are industry standards in processing. Further, the updated MML includes different geometric characteristics based on tooling type, providing more flexibility in describing mill-based tooling.



**Figure 82: Resource Model for Fixturing and Accessories**



**Figure 83: Resource Model for Tooling**

With regard to machine-based resource characteristics, the original MML includes a variety of machines for each type of machining-based process, but lacks several key parameters including

machine footprint, tailstock attachments, number of axes, and workpiece constraints. These elements are included in the updated MML.

#### 4.10.1.4 Common quality measures for manufactured parts

The original MML included a placeholder to describe quality (acceptance) characteristics of the finished products. However, these characteristics were extremely limited in their description. These characteristics will be important in specifying necessary modifications to process parameters to meet quality requirements. Included in the updated MML is an expansive list of standard form, orientation, and location requirements for various features on manufactured parts. These requirements are generic in that various manufacturing processes may be subject to constraints given by the designer. An important element beyond the scope of the C2M2L project is how these requirements are identified in the technical data package and are then accessed and specified using the MML description.

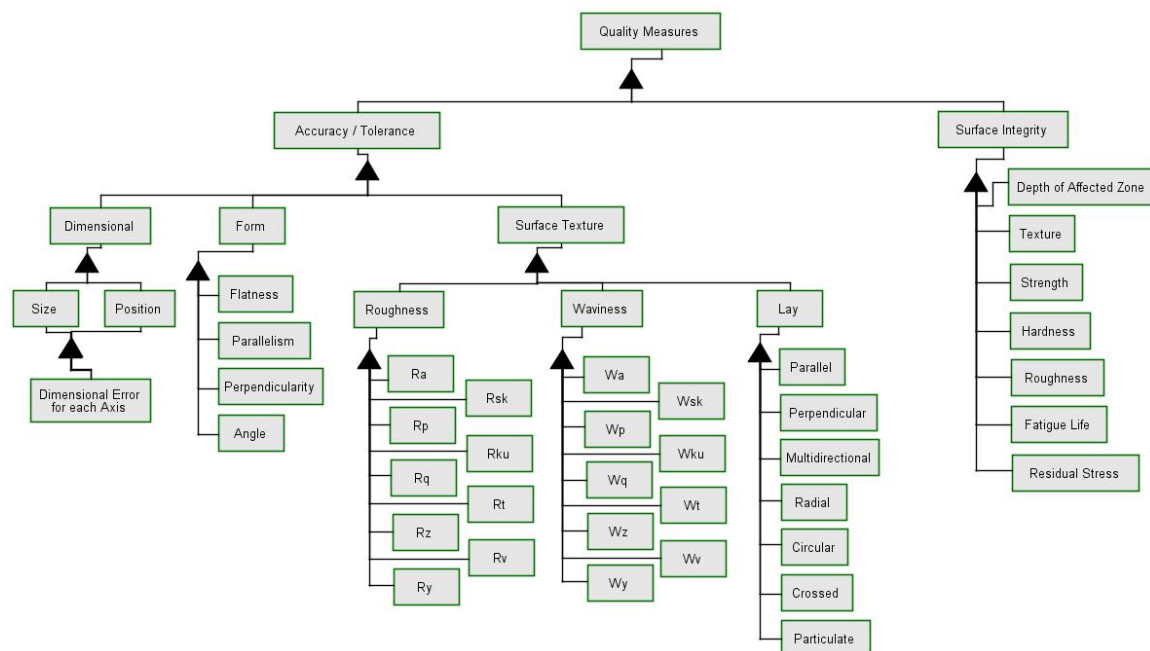
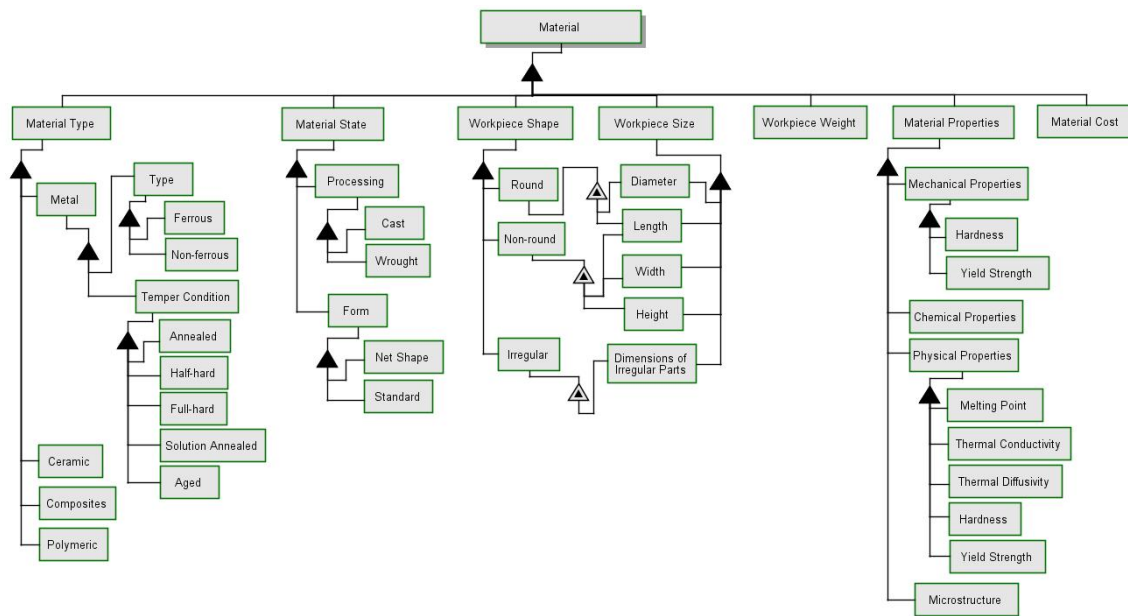


Figure 84: Quality Measures

#### 4.10.1.5 Common Material Models

Material models were developed to describe input material (work) composition, form, pre-processing state, weight, properties, cost, etc. The generic concept model in the original MML has fields to describe thermo-electro-mechanical properties, form, grade and price. To supplement these measures, the updated MML includes an understanding of material state, which can be used to distinguish previous processing methods of the input materials / workpieces. A good example of this may be in machined castings, where the input workpiece for the machining process is not a billet pre-form, but instead is an unqualified cast part. This distinction is not made in the original MML.





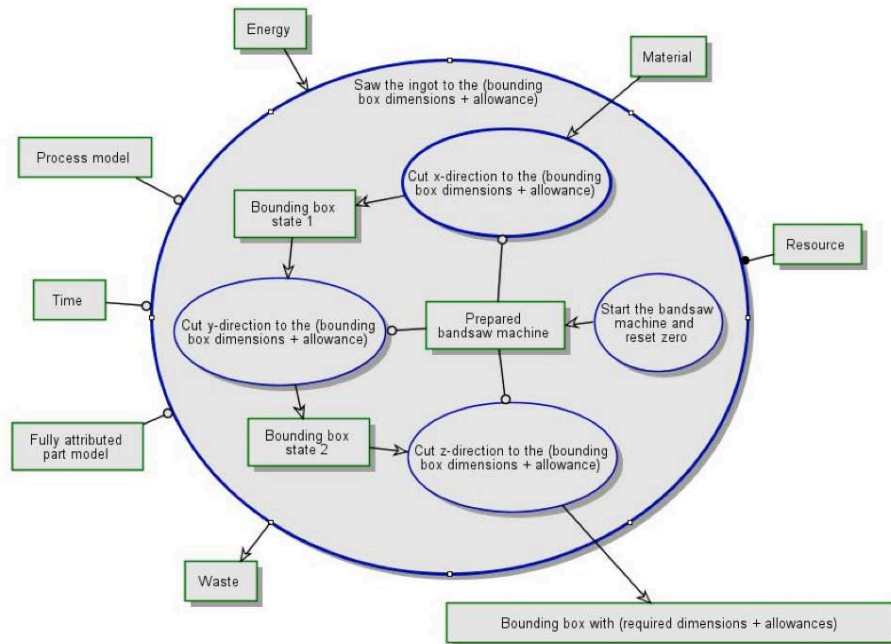
**Figure 85: Common Materials Model**

#### 4.10.1.6 Machining Resource Model Summary

The above description provides an overview of the updated MML with regard to machining-based processes, using milling as an example. Similar OPCAT models and spreadsheet representations were developed for grinding and turning.

#### 4.10.2 Case study – machining of Bradley Fighting Vehicle mounting bracket

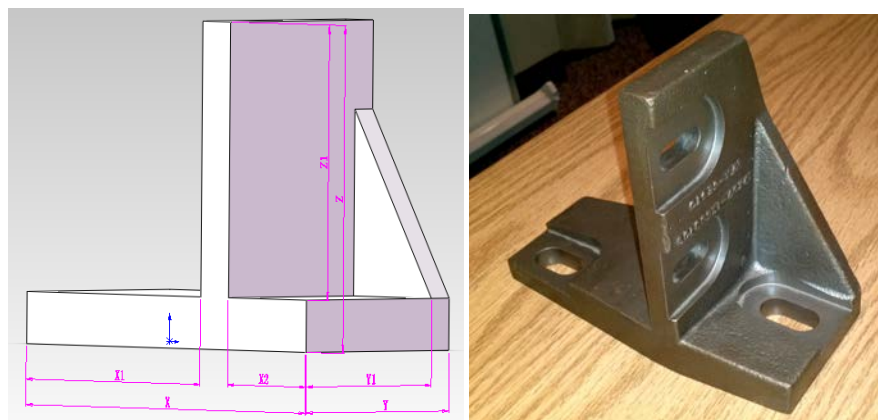
A process plan for machining the Bradley bracket was developed using the MML process descriptions and resource library. The process plan was modeled in OPCAT language as shown in Figure 86. The plan was parameterized to enable the ability to modify part features according to new requirements from designers. The process plan utilizes the parameter selection provided by the final GT MML library database.



**Figure 86: Material Preparation**

#### 4.10.2.1 Bradley bracket example

The Bradley Fighting Vehicle bracket, shown in Figure 87, was modeled in Solidworks according to an example part provided by faculty in the Industrial Engineering department at PSU. While the part itself is an example of a machined casting, this process plan was developed considering that it is entirely machined. The bracket dimensions were defined parametrically with regard to overall feature sizes, feature locations and number of features (e.g., slot dimensions, etc).



**Figure 87: Example Model (Bradley Bracket)**

#### 4.10.2.2 Process plan

The high level process plan for the Bradley bracket was developed according to expert knowledge on machining-based processing. This high-level process plan identified multiple machining operations, including sawing, milling and drilling. For each of the operations, the setup requirements, stock allowances, machining times, tooling requirements were determined

using information provided within the MML. Figure 88 shows the process plan model for the bracket.

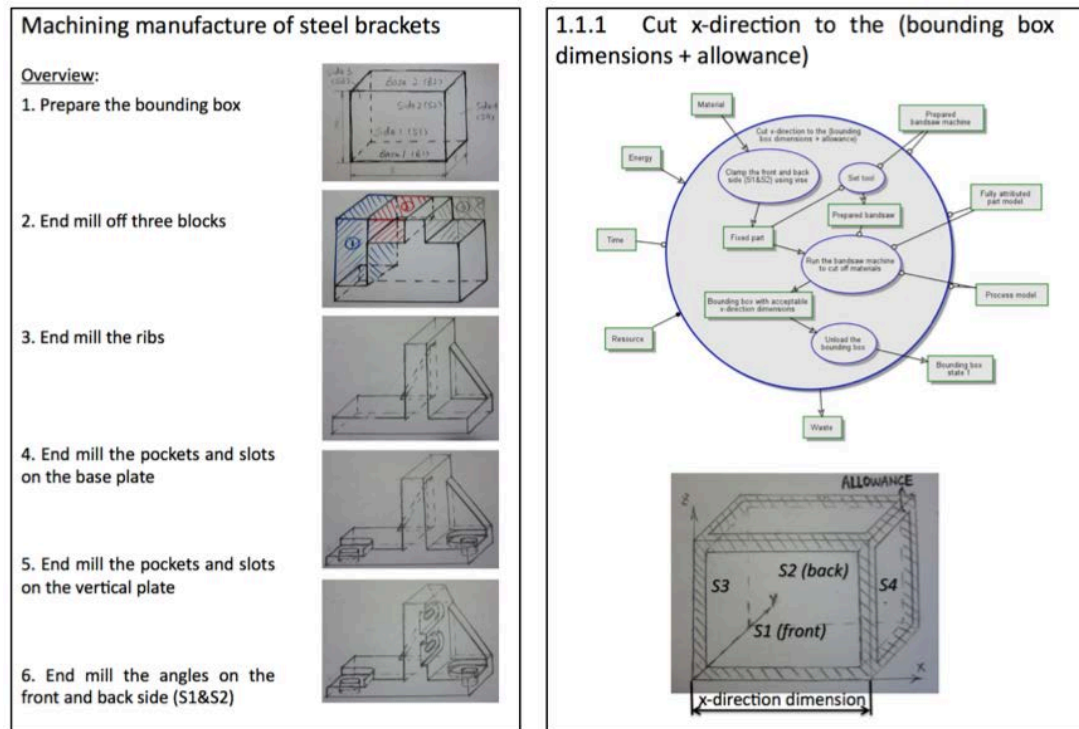
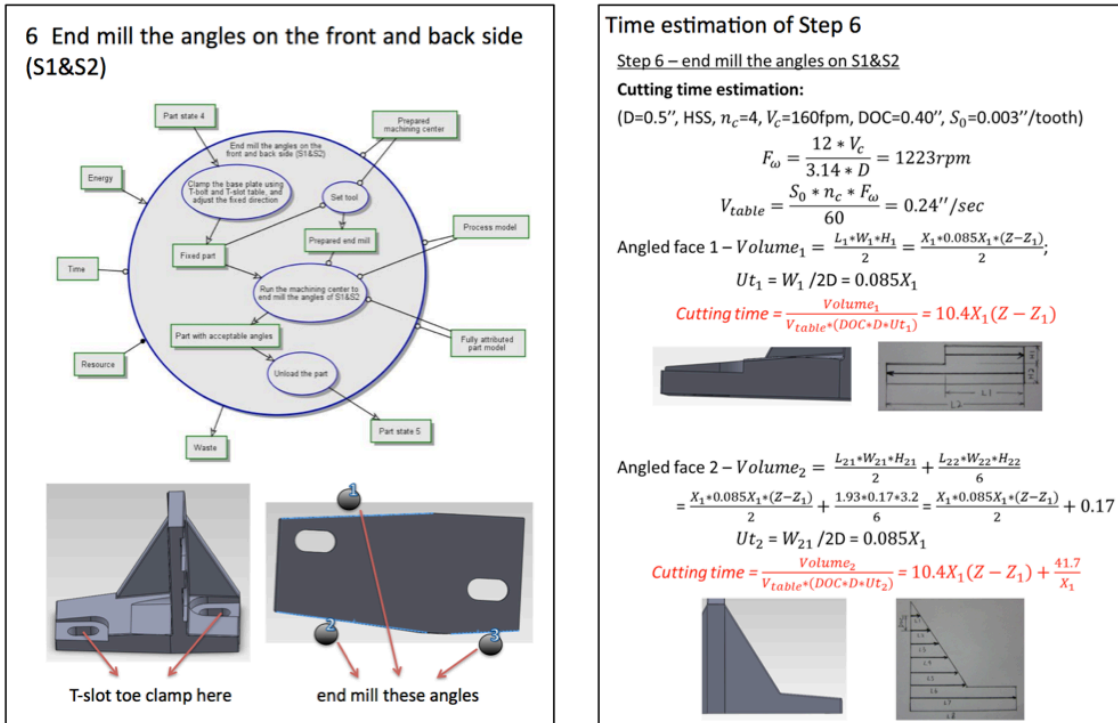


Figure 88: Machining Requirements Example

#### 4.10.2.3 Time estimation and cost estimation

From the process sequence, individual operations were analyzed for their contribution to cost and lead time, according to the resources available within the MML. Processing time and cost is related directly to machining parameters, which were determined using the recommended settings from TechSolve's Machining Data Handbook (MDHB). Figure 89 shows the constraint and cost models. Contributions to lead time associated with requirements for machine setup were collected from standard databases available to describe machine setup. These were included in the MML and are not provided otherwise in the original MML framework. The cost and lead time estimates are defined with respect to part geometry and are thus also parametrically related to feature sizes. A total time and cost estimation for the Bradley bracket is available by summing the individual time and cost elements for each machining operation.



**Figure 89: Constraint and Cost Model**

#### 4.10.2.4 MML integration

The Bradley Fighting Vehicle bracket case study revealed several important aspects of how the MML will need to interface with automated process planning activities. Specifically, integration of the tooling, fixturing and machine resource database is necessary in order to search for compatible process plans for the manufactured design. Additionally, direct linkages with machining parameter selection software (the MDHB) will be needed to specify the process details, including G-code generation and detailed cost estimation. In the final process planning engine that will be developed for IFAB foundry, estimates must be made with regard to machine setup, and these can come from literature surveys of standard machine setup times.

#### 4.11 Additive Manufacturing (Direct Digital Manufacturing)

Table 8 presents a condensed version of the resources modeled for the Direct Digital Manufacturing (DDM) manufacturing process.

**Table 8: Direct Digital Resource Model (Condensed)**

Machine Type	Manufacturer	Model	Type	Machine Dimensions			
				Length (mm)	Width (mm)	Height (mm)	Weight (kgs)
Additive	3D Systems	sPro 250	Selective Laser Melting	1700	800	2025	1225, 1100
Additive	3D Systems	sPro 230	Selective Laser Sintering				
Additive	Arcam	A2	Electron Beam Melting	1850	900	2200	1420

Additive	Arcam	A1	Electron Beam Melting	1850	900	2200	1420
Additive	EOS	EOSINT M270	Direct Metal Laser Sintering	2000	1050	1940	1130
Additive	EOS <sup>4</sup>	EOSINT M280	Direct Metal Laser Sintering	2200	1070	2290	1250
Additive	ExOne	M-Print	Digital Part Materialization	2252	2584	2114	
Additive	ExOne	M-Lab	Digital Part Materialization	965	711	1066	
Additive	ExOne <sup>3</sup>	M7	Digital Part Materialization	2625	2450	2150	2500
Additive	Optomec	LENS 750	Direct Metal Laser Sintering				
Additive	Optomec	LENS 850R	Direct Metal Laser Sintering				
Additive	Optomec <sup>2</sup>	LENS MR-7	Direct Metal Laser Sintering	1499	2032	2350	
Additive	Phenix Systems	PXL	Selective Laser Sintering	2400	2200	2400	5000
Additive	Phenix Systems	PXM	Selective Laser Sintering	1200	1500	1950	1500
Additive	Phenix Systems	PXS	Selective Laser Sintering	1200	770	1950	1000
Additive	POM Group	DMD 105D	Direct Metal Deposition	2800	2890	3370	
Additive	POM Group	DMD 44R	Direct Metal Deposition	2750	4480	3660	
Additive	POM Group	DMD 66R	Direct Metal Deposition	2744	4877	3658	
Additive	POM Group	DMD 505D	Direct Metal Deposition	2750	4880	3660	
Additive	POM Group	IC 106	Direct Metal Deposition	2950	2250	2350	
Additive	ReaLizer	SLM 100	Selective Laser Melting	900	800	2400	500
Additive	ReaLizer	SLM 250	Selective Laser Melting	1800	1000	2200	800
Additive	ReaLizer <sup>5</sup>	SLM 50	Selective Laser Melting	800	700	500	80
Additive	Renishaw	AM125	Selective Laser Melting	1350	800	1900	1125
Additive	Renishaw	AM250	Selective Laser Melting	1700	800	2025	1225
Additive	Sciaky <sup>6</sup>	"DM Solution"	Electron Beam Direct Manufacturing				
Additive	SLM Solutions GmbH	SLM 280HL	Selective Laser Melting	1800	1000	2400	1000

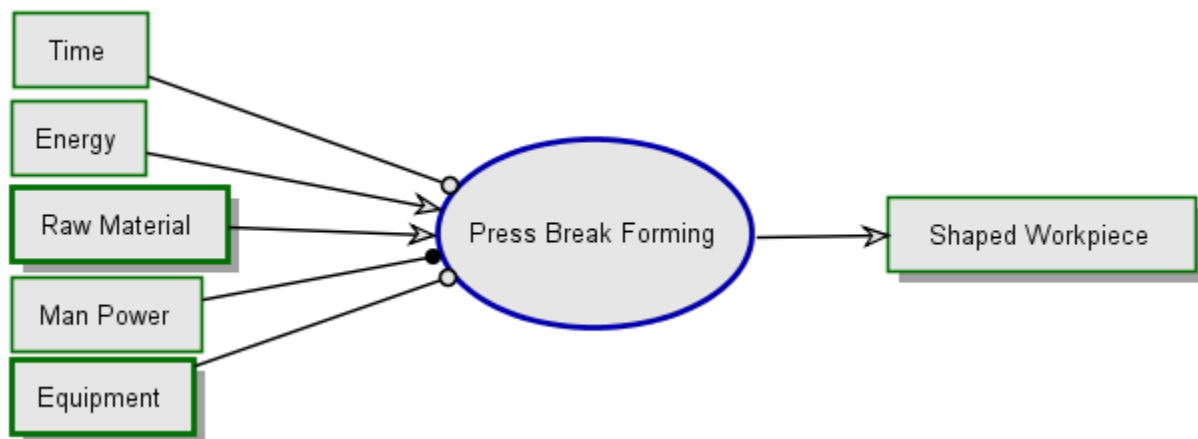
## 4.12 Assembly

Information provided to the ARL PSU team from the iFAB Foundry performer included: portable air compressor, suspension trolley, and portable grease pump, full metric and English tool sets (wrenches, torque wrenches, etc.), small hand/power tools and accessories (i.e. grinders, air ratchets, pneumatic drill, torque multipliers, torque/impact wrenches, pipe spanners etc.), , and portar power jacks. Each of these items were characterized and entered into the MML database with the exception of any tools that would be considered a duplication in the Boeing MCPML.

## 4.13 Forming

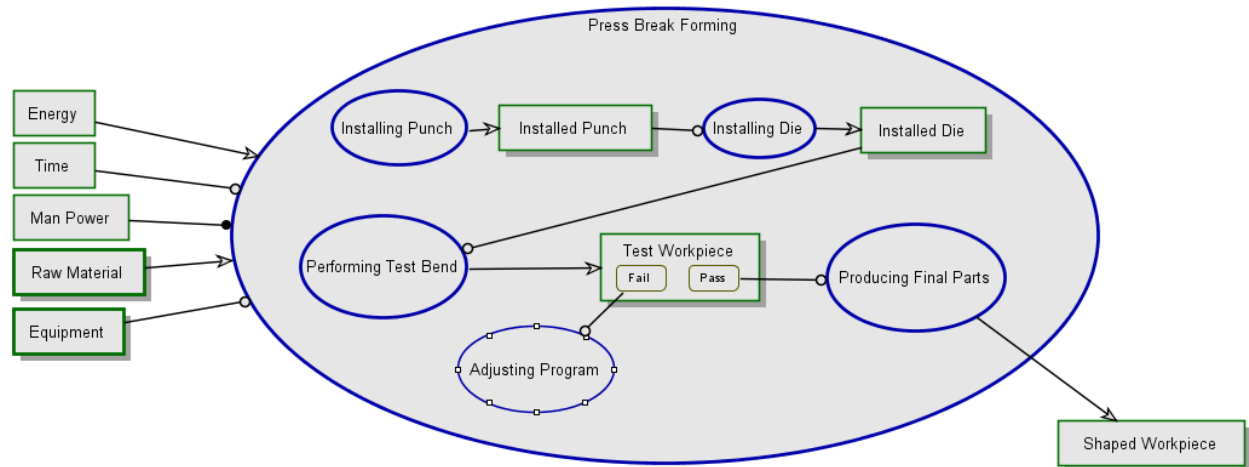
### 4.13.1 Press Break Forming

Figure 90 displays the top level process model for press break forming. The process requires two major inputs in the form of raw materials and energy needed to complete the process. In addition, there are two non-intelligent enablers for time and equipment. The process also requires an intelligent enabler in the form of manpower. The output of the press break forming process is a shaped workpiece.



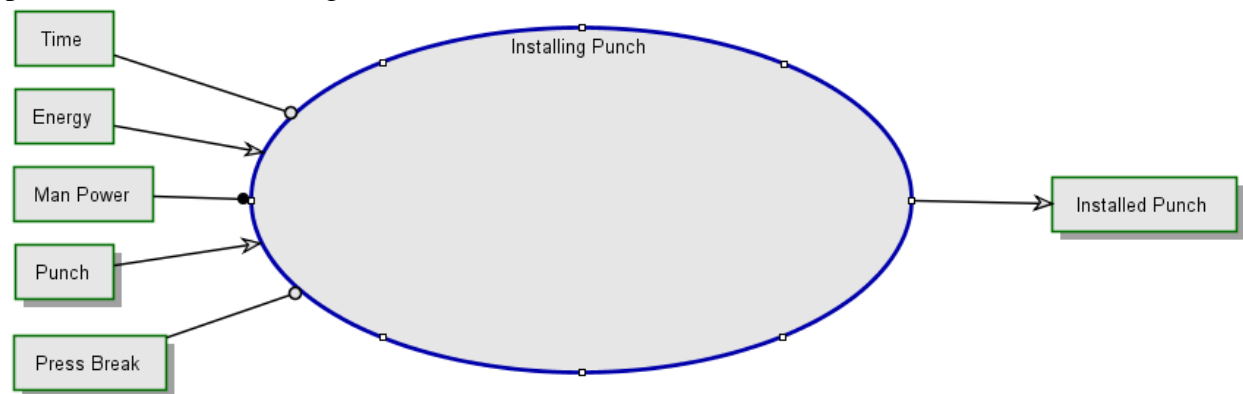
**Figure 90: Press Break Forming Process**

Greater detail of press break forming process can be obtained by “in-zooming” on the Press Break Forming process in the OpCat modeling software. The in-zoomed press break forming model is shown in Figure 91, where it outlines the multiple sub-processes necessary to produce a press break formed part as well as each sub-processes output. Each sub-process is completed in the order shown in Figure 91.



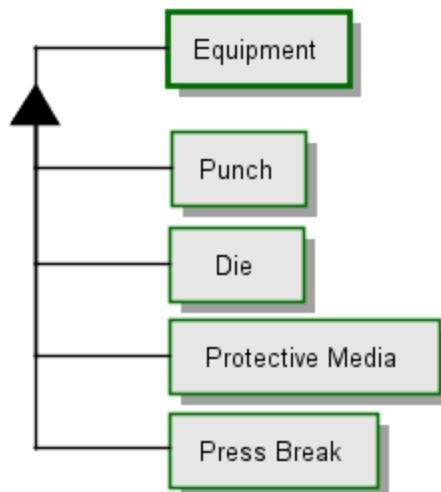
**Figure 91: In-Zoomed Press Break Forming Process**

Each sub-process can be further in-zoomed to outline the specific equipment or raw material needed to complete that sub-process. The in-zoomed sub-process also includes that specific sub-processes output that is used by other sub-processes. The in-zoomed “Installing Punch” sub-process can be seen in Figure 92.



**Figure 92: In-Zoomed Sub-Process of Installing Punch**

Figure 93 displays the unfolded equipment object. The black triangle represents an aggregation participation meaning that punch, die, protective media, and press break are part of a larger equipment object. The individual piece of equipment needed for each sub-process is pulled from this object.



**Figure 93: Press Break Forming Equipment**

#### 4.14 Manufacturing Model Library Database Structure

The data storage mechanism for the ARL PSU MML was a PostGres database with little to no logic built upon the data and information included in the database. The project team made the decision to keep the developed MML simple and easily subsumed into one of the other more complete library structures being developed in the IFAB program.

The following tables show the database structure used in this work.

**Resource Table - Top-level resource, subclassed in other tables (MaterialHandler, Labor, etc.)**

Name	Description	Type
id	The unique identifier for this entity	UUID

**MaterialHandler Table - Material handling availability at each manufacturing node**

Name	Description	Type
model	The model number	Text
description	The description of this material handling device	Text
type	The type of this material handling device	Text
max_lift_height	The maximum lift height of this device (m)	Decimal
min_lift_height	The minimum lift height of this device (m)	Decimal
max_lift_weight	The maximum lift weight of this device (kg)	Decimal
operating_cost	The operating cost of this device (USD/h)	Decimal
purchase_cost	The purchase cost of this device (USD)	Decimal
span	The span / reach of this device (m)	Decimal
max_force	The maximum thrust / pull of this device (kg)	Decimal
travel_speed	The travel speed of this device (km/h)	Decimal
turning_radius	The turning radius of this device (m)	Decimal
vehicle_height	The height of this device (m)	Decimal
vehicle_width	The width of this device (m)	Decimal



vehicle_length	The length of this device (m)	Decimal
vehicle_weight	The weight of this device (kg)	Decimal
resource_id	The foreign key of the resource	UUID
manufacturingnode_id	The foreign key of the manufacturing node containing this resource	UUID

**Labor Table - Labor availability at each manufacturing node**

Name	Description	Type
name	The name / type of labor	Text
operating_cost	The operating cost for this labor (USD/h)	Decimal
resource_id	The foreign key for the resource	UUID
manufacturingnode_id	The foreign key of the manufacturing node containing this resource	UUID

**Tooling Table - Tooling for machines available at each manufacturing node**

Name	Description	Type
corner_radius	The corner radius of the tool (mm)	Decimal
flutes	The number of flutes on the tool	Integer
helix_angle	The helix angle (degrees)	Decimal
lathe_process	Can this tool be used on a lathe?	Boolean
mill_process	Can this tool be used on a mill?	Boolean
overall_length	The overall length of this tool (mm)	Decimal
reach_length	The maximum reach of this tool (mm)	Decimal
shank_diameter	The shank diameter (mm)	Decimal
tolerance_model	The tolerance of this tool (mm)	Decimal
hardness	The Brinell hardness of this tool	Integer
resource_id	The foreign key for the resource	UUID
coat_material_id	The foreign key for the tool coating	UUID
tool_material_id	The foreign key for the tool material	UUID
tool_type_id	The foreign key for the tool type	UUID

**ToolingType Table - The type of tool (drill, punch, end mill, etc.)**

Name	Description	Type
id	The unique identifier for this entry	UUID
name	The name of this tool type	Text

**ToolingCoating Table - The coating applied to the tool**

Name	Description	Type
id	The unique identifier for this entry	UUID
name	The name of the tool coating	Text

**ToolingMaterial Table - The material of the tool (e.g., solid carbide)**

Name	Description	Type
id	The unique identifier for this entry	UUID
name	The name of the tool material	Text

**Coolant Table - The list of available coolants**

Name	Description	Type
name	The name of the tool material	Text
resource_id	The foreign key of the resource	UUID

**ToolingOption Table - Available tooling options and performance data**

Name	Description	Type
id	The unique identifier for this entry	UUID
chiploadperflute	The amount of material removed by each flute (mm^3)	Decimal
feedmaximum	The maximum feed rate (mm/min)	Decimal
feedminimum	The minimum feed rate (mm/min)	Decimal
speed	The cutting speed (mm/min)	Decimal
coolant_id	The foreign key of the coolant used in this option	UUID
material_id	The foreign key of the material cut in this option	UUID
tooling_id	The foreign key of the tool used in this option	UUID

**Machine\_Tooling Table - Identifies which tools are available to each machine**

Name	Description	Type
machine_id	The foreign key of the machine	UUID
tooling_id	The foreign key of the tooling	UUID

**Machine Table - The machines available at each manufacturing node**

Name	Description	Type
name	The name of this machine	Text
description	A description of this machine	Text
machine_size_x	The machine length (mm)	Decimal
machine_size_y	The machine width (mm)	Decimal
machine_size_z	The machine height (mm)	Decimal
table_size_x	The table length (mm)	Decimal
table_size_y	The table width (mm)	Decimal
table_size_z	The table height (mm)	Decimal
max_diameter	The maximum workpiece diameter (mm)	Decimal
max_length	The maximum workpiece length (mm)	Decimal
max_width	The maximum workpiece width (mm)	Decimal
max_height	The maximum workpiece height (mm)	Decimal
max_weight	The maximum workpiece weight (kg)	Decimal
resource_id	The foreign key of the resource	UUID
manufacturingnode_id	The foreign key of the manufacturing node containing this resource	UUID

**Machine\_Processes Table - Assigns the processes each machine can perform (milling, facing, painting, etc.)**

Name	Description	Type
machine_id	The foreign key of the machine	UUID
process_id	The foreign key of the process	UUID

#### **Process - The list of supported manufacturing processes**

Name	Description	Type
id	The unique identifier for this entry	UUID
name	The name of this process	Text

#### **Process\_Feature - Identifies manufacturing features that can be produced by a process (pocket, edge, etc.)**

Name	Description	Type
process_id	The foreign key of the process	UUID
features_id	The foreign key of the feature	UUID

#### **Feature - The list of supported manufacturing features**

Name	Description	Type
id	The unique identifier for this entry	UUID
name	The name of this feature	Text

#### **CatalogItem Table - Consumables that are purchased from some supplier**

Name	Description	Type
id	The unique identifier for this entry	UUID
item_id	The foreign key of this item	UUID
item_type	The type of this item	Integer
lead_time	The lead time of this item (days)	Integer
price	The purchase price of this item (USD)	Decimal
quantity	The quantity of this item obtained in a single purchase	Integer
serial_code	The serial code used for ordering this item from the supplier	Text
shippingcost	The shipping cost of this item (USD)	Decimal
vendor_name	The name of the vendor	Text

## **5.0 CONCLUSIONS**

The main conclusion stemming from this effort is that detailed manufacturing models (process and resource models) provide an opportunity for cost and lead time reductions in the design and construction of military ground vehicles.

A fully characterized manufacturing model should be capable of providing the necessary information and logic for a wide range of analyses and queries. At a high-level, these models should be able to support plant layout, material flow, scheduling, manufacturability feedback, cost, time (makespan and processing time), and human work instruction generation. The

developed methodology of defining and linking process models with resource models enables these analyses to be performed.

The project team proposed to develop the database structure with little analysis logic surrounding the information in anticipation of the data being subsumed into one of the existing (developing under iFAB) library infrastructures. This proved to be a wise decision in that little time was spent on query languages and interfaces and was directly spent working with subject matter experts in each of the process classes gathering data and developing models. This provides a much richer set of models that can support the various analyses required of the future performers in the program.

As with any project of this magnitude, there are lessons learned. In this project the key lesson learned was to identify the modeling technique and tool as early as possible and potentially develop a modeling tool specifically aimed at eliciting the information from the subject matter experts and practitioners. A focused information elicitation tool would have greatly increased the efficiency of the data collection efforts and provided a more streamlined approach to gathering and storing the information.

## 6.0 REFERENCES

Randall H. Wilson, On geometric assembly planning, Stanford University, Stanford, CA, 1992

B. Romney, C. Godard, M. Goldwasser, and G. Ramkumar, An efficient system for geometric assembly sequence generation and evaluation, in ASME Int. Comput. Eng. Conf., 1995, pp. 699–712.

<http://www.opencascade.org/>

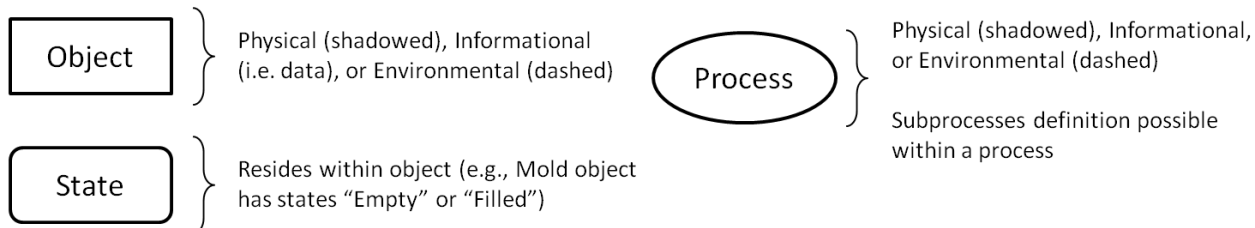
<http://www.opcat.com/>

## 7.0 APPENDIX

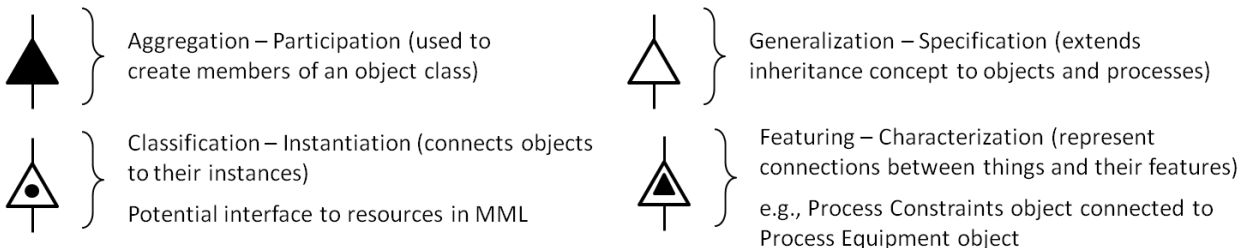
### 7.1 Object Process Methodology Definitions

#### Process Model Glossary

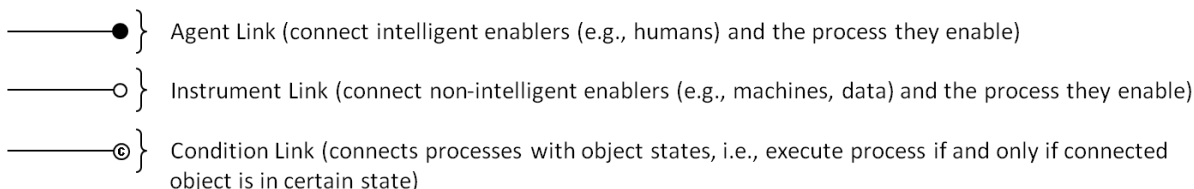
##### Main Entities



##### Structural Relations (connection/association between 2 entities), 4 types



##### Procedural Links (connects a process to an enabler not changed by that process), 4 types



**Figure 94: OPCAT OPM Process Model Glossary of Object, Relation, and Link Symbols**

### 7.2 Welding Process Parameters

Table 9 shows the welding process parameters that the project team identified to develop the welding manufacturing model.

Table 9: GMAW Paramters

*Blanked areas mean this process is not appropriate for this material. Calculation columns are hidden. (This matrix can be expanded as we determine likely types of welds and processes requested. Can be simplified as a data structure*

Material	Gauge/in.	Joint Type	Sides Welded		Cost per ft of weld	Labor hours per ft of weld
Al	1/2"	Butt	Single		31.7121368	0.525866609
Al	1/4"	Butt	Single		17.2256558	0.310146228
Al	1/8"	Butt	Single		12.5804206	0.226677405
Al	3/16"	Butt	Single		18.6041906	0.32709915
Al	3/8"	Butt	Single		24.06842	0.40343327
Al	5/16"	Butt	Single		20.7024263	0.359703484
Al	7/16"	Butt	Single		29.2813119	0.507505289
Plain:Carbon Steel	14	Butt	Single		12.7464094	0.249236349
Plain:Carbon Steel	16	Butt	Single		14.6805864	0.299659856
Plain:Carbon Steel	18	Butt	Single		14.7544384	0.306543991
Plain:Carbon Steel	20	Butt	Single		15.214818	0.321446448
Plain:Carbon Steel	22	Butt	Single		18.3120588	0.392983854
Plain:Carbon Steel	1/4"	Butt	Single		32.1352005	0.648752358
Plain:Carbon Steel	1/8"	Butt	Single		18.46736	0.38221857
Plain:Carbon Steel	3/16"	Butt	Single		25.5453286	0.522220869
Plain:Carbon Steel	3/8"	Butt	Single		42.8375734	0.8394921
Plain:Carbon Steel	5/16"	Butt	Single		37.9844548	0.756638041
Al	1/2"	Butt	Double		15.9228383	0.264040517
Al	1/4"	Butt	Double		8.74957434	0.15753522
Al	1/8"	Butt	Double		6.70099895	0.120740403
Al	3/16"	Butt	Double		9.56739999	0.168214165
Al	3/8"	Butt	Double		12.1201297	0.203156815
Al	5/16"	Butt	Double		10.4564619	0.181680433
Al	7/16"	Butt	Double		14.7190069	0.255110628
Plain:Carbon Steel	14	Butt	Double		7.53380831	0.147311985
Plain:Carbon Steel	16	Butt	Double		9.38152397	0.191495492
Plain:Carbon Steel	18	Butt	Double		10.4580008	0.217279522
Plain:Carbon Steel	20	Butt	Double		12.7395173	0.269150284
Plain:Carbon Steel	22	Butt	Double		17.291907	0.371091002
Plain:Carbon Steel	1/4"	Butt	Double		16.3227066	0.32952632
Plain:Carbon Steel	1/8"	Butt	Double		9.83669496	0.203589873
Plain:Carbon Steel	3/16"	Butt	Double		13.1369529	0.268557554
Plain:Carbon Steel	3/8"	Butt	Double		21.5717087	0.422742877
Plain:Carbon Steel	5/16"	Butt	Double		19.185336	0.382165681
Al	1/2"	Tee	Single		4.16865452	0.069126727